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Observing Marine Aerosols and Clouds from Ships

WORKSHOP REPORT

March 18-20, 2024

DISCLAIMER

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About BER: The BER program advances fundamental research and scientific user facilities to support U.S. Department of Energy missions in scientific discovery and innovation, energy security, and environmental responsibility. BER seeks to understand biological, biogeochemical, and physical principles needed to predict a continuum of processes occurring across scales, from molecular and genomics-controlled mechanisms to environmental and Earth system change. BER advances understanding of how Earth's dynamic, physical, and biogeochemical systems (atmosphere, land, oceans, sea ice, and subsurface) interact and affect future Earth system and environmental change. This research improves Earth system model predictions and provides valuable information for energy and resource planning.

Cover Image: This image shows the bow of a commercial ship during the Marine ARM GPCI Investigation of Clouds (MAGIC) campaign (2012-2013). The field campaign measured the properties of open-ocean clouds and precipitation, aerosols, radiation, and meteorological conditions in the Eastern North Pacific.

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Executive Summary

A March 2024 DOE workshop examined the use of commercial ships as observational platforms, expanding the reach of shipborne atmospheric observations. Photo courtesy of the Atmospheric Radiation Measurement (ARM) user facility.

Oceans cover approximately 71% of the Earth's surface and the response of marine low clouds to changes in greenhouse gases and aerosol concentrations is one of the largest uncertainties in current Earth system models. Despite their critical role in the Earth's climate, marine regions are insufficiently sampled because of their vast expanse and the expense of dedicated shipborne research campaigns. Leveraging commercial ships as observational platforms could expand the reach of shipborne observations but has significant logistical challenges.

The U.S. Department of Energy's (DOE) Biological and Environmental Research (BER) program organized a virtual workshop on "Observing Marine Aerosols and Clouds from Ships" to identify scientific priorities for shipborne measurements of marine aerosols, clouds, greenhouse gases, and other environmental factors; research opportunities that would be enabled by different types of shipborne measurements; past and current shipborne observing technologies, including their challenges and limitations; logistical challenges and considerations for deploying instrumentation on commercial/non-research vessels; and opportunities for coordination with other federal agencies and/or international efforts.

The following summarizes key highlights and findings from the workshop discussion:

Logistical challenges: Key logistical challenges that would need to be addressed for a successful atmospheric observational program on commercial ships are developing and maintaining good relationships with shipping companies; plans for instrument installation and maintenance in port; hardening of instrumentation for marine environments; instrument location on the ship, impacts of ship motion and exhaust on measurements; data quality control; data transfer and remote monitoring of instruments; legal issues; and potential hazards and risks.

Coordination with existing activities: Participants identified several existing programs supported by other federal agencies that are conducting measurements of oceanic properties, surface meteorology, and greenhouse gases on commercial ships. It would be valuable for a DOE/BER shipborne observations program to coordinate with and learn from the expertise in these programs. Existing DOE activities have strong expertise in data ingestion, curation, distribution, and archiving that could be leveraged for managing data from a shipborne program.

High-priority feasible instrumentation: Participants discussed the challenges of deploying unattended instrumentation for measuring aerosol, ocean, greenhouse gas, cloud, and radiation properties on commercial ships. Since existing programs exist for the deployment of ocean measurements and greenhouse gas measurements on commercial ships, the discussion focused primarily on measurements of aerosol, cloud, atmospheric state, and radiation properties. Participants described the following set of measurements as both of high scientific priority and feasible for unattended operation on ships with little or no instrument development:

- Surface meteorology
- Aerosol size distribution from optical particle counter
- Carbon monoxide mixing ratios
- Aerosol number concentration
- Aerosol optical properties (aerosol extinction, scattering, and/or absorption)
- Broadband shortwave and longwave radiation
- Ship position/navigation
- Cloud-base height from ceilometer
- Cloud-base temperature
- Bulk surface fluxes
- Sky conditions/cloud fraction from sky imager
- Liquid water path/integrated water vapor from microwave radiometer.

Participants also identified a second set of measurements that had high scientific priority but needed moderate instrument development to be feasible for unattended shipborne observations. Of these, turbulence/updraft measurements from Doppler lidar and mobility-based aerosol size distributions were felt to be the most important and would be the highest priority for instrument development to make them suitable for unattended shipborne operation.

Workshop participants emphasized that designing modular instrument packages that would allow easy switch out of instruments in port for calibration and maintenance would be critical for addressing logistical and instrument challenges. Such packages would need environmental (temperature and humidity) control for shipborne observations and integrated data systems. Many of the identified aerosol measurements will require a well-characterized inlet that pre-conditions the air samples. Phased testing of the instrument packages (i.e., moving from laboratory tests to local outdoor deployments to deployment on local marine platforms such as a barge or ferry with onboard technicians) would be important for ensuring that they are suitable for unattended operations on ocean-going vessels.

Scientific questions that can be addressed with the most feasible measurements: The initial workshop discussion of scientific questions that could be addressed by measurements on commercial ships was based on science topics proposed by participants in their pre-workshop responses. During discussion of each topic, participants considered the following questions: Why is this question critical for improving Earth system predictability and/or meeting BER scientific goals? Why is it suited to opportunistic measurements? Which measurements would be necessary? Which region(s)/shipping lane(s) would be appropriate? What type of measurement statistics and/or length of measurement record would be necessary?

The feasibility of addressing each of the discussed science topics with autonomous observations on commercial ships is broad – some topics would only require measurements that are considered currently feasible with minor instrument development or modification; others would require measurements that would need moderate or significant investment in instrument development to be feasible to operate on commercial ships; while others are more suitable to traditional targeted field campaigns with advanced instrumentation and dedicated instrument technicians.

Workshop participants synthesized the discussions about logistics, instrumentation, and science questions to consider which science questions could most quickly be addressed by deploying a set of the most feasible and moderately feasible instruments (discussed above). They noted that deployment of this set of the most feasible measurements on commercial ships would be valuable to:

- Provide information on the background state of oceanic aerosol and information on environmental variability within, near, and outside shipping lanes;
- Provide information on aerosol sources when combined with back trajectory calculations;
- Enable statistical analysis and compositing of data (e.g., by meteorological conditions) for understanding environmental controls on different processes as well as for validation of model simulations and testing of satellite-retrieval assumptions;
- Fill critical observational gaps such as cloud-base height and aerosol properties under clouds that are unobtainable from satellites alone; and
- Identify variability, phenomena, or processes that are not well captured in current models, which could lead to development of more targeted short-term research campaigns with advanced instrumentation to address these questions.

Participants identified the following set of scientific research topics that could potentially be addressed with this set of measurements on commercial ships:

- Environmental controls on variability in cloud properties, cloud radiative cooling, and aerosol-cloud interactions, including cloud processing of aerosols and impacts on precipitation;
- The effects of marine boundary-layer structure and mesoscale cloud organization on surface fluxes and their relationships with aerosols and clouds;
- Environmental controls of marine boundary-layer decoupling;
- The variability of aerosol in the marine boundary layer and how aerosol properties differ between the remote ocean, traditional shipping lanes, and the coastal sites that are often used as proxies for marine aerosol properties;
- Constraints on estimates of the direct radiative impacts of aerosol in different ocean regions and identification of regions that are poorly represented in models;
- The environmental conditions under which ship tracks will form;

- Initialization and constraint of parcel models, predictions of cloud condensation nuclei, and mechanistic evaluation of the aerosol indirect effect; and
- Environmental conditions and locations conducive to newly formed particles as well as their growth and contribution to cloud condensation nuclei budgets.

Key elements of a pilot program: Participants also identified key elements that they thought would be necessary for a successful pilot program. These elements include: a comprehensive science plan; a science team with necessary breadth of expertise; metrics for success; a plan for instrument development, hardening, packaging into modules, and operational configuration; phased testing of instrument packages and autonomous operations; plans for instrument maintenance, calibration, data processing, archiving, and distribution; collaboration with or leveraging of existing activities; and a communication plan for engaging the broader scientific community.

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Introduction and Workshop Overview

During the year-long Marine ARM GPCI Investigation of Clouds (MAGIC) campaign (2012-2013), atmospheric instruments were deployed on a commercial ship, which collected data in the open ocean between California and Hawaii. Image courtesy of Mike Ritsche, Argonne National Laboratory.

The mission of the BER program is to support transformative science and scientific user facilities to achieve a predictive understanding of complex biological, earth, and environmental systems for energy and infrastructure security, independence, and prosperity. In 2018, BER hosted a workshop to facilitate input and discussion from the scientific community on the highest-priority opportunities for BER observational capabilities to best address the BER goal of improving the predictability of Earth system models (U.S. DOE 2019). One of the key areas identified in that workshop was marine regions. As discussed in the workshop report, "Approximately 80% of all low clouds on Earth occur over the oceans, and uncertainty in how marine low clouds are expected to change with increasing greenhouse gases remains the largest source of uncertainty in cloud feedback and climate sensitivity. In addition, although most anthropogenic aerosols originate from emissions over land, models show that a disproportionately large fraction of the global aerosol indirect forcing is associated with aerosol-cloud interactions over remote marine regions. Earth system models suffer from major biases in their representation of clouds, precipitation, and aerosols in marine regions. There is a great need for surface, and in situ observations of clouds, aerosols, and precipitation in marine regions, but logistical and measurement challenges mean that such observations are mostly restricted to relatively short campaigns with research vessels and/or aircraft." (U.S. DOE 2019).

Targeted field campaigns on dedicated oceanographic research vessels allow deployment of complex instruments to particular marine regions of interest to address important science questions. However, the expense of these dedicated campaigns and the small number of available research vessels limit the amount of data that can be collected. The ability to leverage the vast number of commercial vessels that regularly sail the world's oceans would provide opportunities to greatly expand the reach of shipborne observations, but implementing such observations has significant challenges. From October 2012 to September 2013, the BER Atmospheric Radiation Measurement (ARM) user facility deployed its mobile facility on a commercial ship transiting between Los Angeles and Hawaii for the Marine ARM GPCI Investigation of Clouds (MAGIC) campaign (Lewis 2016). Deployment of the full ARM mobile facility on a commercial ship required engineering of the ship infrastructure to support the instrumentation; two full-time technicians onboard the ship for each voyage; and significant support from ARM instrument mentors, the ARM Data Center, and other staff. Such complex deployments on commercial ships are not sustainable as a long-term marine measurement strategy. However, a limited set of instruments might be feasible to deploy for longer measurement periods. The ideal set of measurements and deployment strategies would depend on the overall goals of such a measurement program.

Based on congressional direction encouraging BER to develop a pilot program in environmental measurements from commercial or other non-dedicated ocean vessels, BER organized a workshop to obtain information from the research community on the highest scientific priorities, technical challenges, and opportunities for deploying shipborne instrumentation on commercial ocean vessels, as well as to understand ongoing activities and areas for cooperation with other agencies and/or international activities.

The primary goals of the workshop were to inform BER about:

- scientific priorities for shipborne measurements of marine aerosols, clouds, greenhouse gases, and other environmental factors;
- research opportunities that would be enabled by different types of shipborne measurements;
- past and current shipborne observing technologies, including their challenges and limitations;
- logistical challenges and considerations for deploying instrumentation on commercial/non-research vessels; and
- opportunities for coordination with other federal agencies and/or international efforts.

Although originally planned as in-person, the workshop was changed to virtual and conducted over Zoom because of uncertainty about travel planning for federal attendees related to the multiple continuing resolutions that were passed at the start of fiscal year 2024. Attendees from the scientific community were invited based on their expertise and included scientists from DOE national laboratories, federal research laboratories, academic institutions, and industry with expertise in instrumentation and marine atmospheric research. During planning for the workshop, BER discussed the workshop with program managers from the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA), who suggested potential attendees and attended as observers.

Several factors were considered when developing the workshop agenda. A foundation was the knowledge that identifying scientific questions suitable for a potential pilot program would require understanding the similarities and differences between making routine observations on commercial/non-dedicated research vessels and making targeted field-campaign measurements on dedicated research vessels. In preparation for the workshop, invited attendees were asked to think about these differences and to provide brief input in several topical areas (measurement needs, scientific questions, logistical challenges, data, and existing activities) to provide background to all attendees and to inform the organization of the workshop.

The BER program managers synthesized the responses to identify key areas for discussion during the workshop and to organize the agenda into sessions. Sessions on the first day of the workshop were designated for discussion about logistics and instrumentation and on the second day for science questions. The program managers identified facilitators for each of these sessions and provided worksheets to help them organize session discussions and capture key findings. The agenda for the third day was reserved for discussion of topics that arose during the first and second days.

The workshop opened with a plenary session in which the BER program managers discussed the charge and agenda for the workshop. The sessions on the first day of the workshop were designed to give attendees background for the science discussions on the second day. These sessions focused on the logistics of working on commercial ships and the feasibility of unattended/autonomous operation of various instrumentation. The sessions on the second day of the workshop focused on identifying and discussing science questions that might be well suited for an initial pilot project.

The third day of the workshop opened with an interactive brainstorming session using the XLeap platform. This session allowed attendees to propose, discuss, merge, and then rank additional discussion topics. Based on this ranking process, afternoon breakout sessions focused on science that could be done using a limited suite of the most feasible instruments and on key elements for a successful pilot program. The workshop ended with a brief discussion of the planned workshop report.

The workshop agenda, including goals and facilitators for each session, a list of acronyms, tables summarizing the measurements discussed during the breakout sessions, the background material and guiding questions, and the final list of attendees, along with brief biographies indicating their relevant expertise; are included in the appendices.

Ships of Opportunity – Background and Logistical Issues

The goal of the first discussion session was to give workshop attendees background on working on/with commercial ships (also known as ships of opportunity) instead of dedicated research vessels. The expected outcomes were for attendees to document logistical challenges that would need to be addressed in a pilot project and to note potential solutions.

A plenary presentation was given by Kerry Strom (Woods Hole Oceanographic Institute [WHOI]) about the Science Research on Commercial Ships (Science RoCS) initiative. This initiative focuses on expanding oceanic observations (such as Argo floats, meteorological sensors, and measurements of partial pressure of CO_2 and ocean currents) through collaborations between research institutions and the commercial shipping industry. The presentation discussed the history and structure of the Science RoCS program, the sensors currently deployed and planned, and the challenges and successes of deploying instruments on commercial ships. While focused primarily on oceanic measurements, the Science RoCS initiative has many useful lessons for deploying atmospheric measurements on commercial ships.

Commercial ships (also called ships of opportunity), like this American President Lines container ship, can offer an alternative to research vessels. Image courtesy of Mike Ritsche, Argonne National Laboratory.

After the Science RoCS initiative presentation, workshop participants broke up into two assigned breakout sessions to discuss logistical issues, challenges, and potential solutions associated with making measurements on ships of opportunity. Key findings from those discussions are summarized below.

Relationships with Shipping Companies

Successful deployment of a pilot program requires developing and maintaining good relations with shipping companies, captains, and crews. Measurements, instrument operation/maintenance, and hazards must not interfere with ship operations and must minimize impact on the ship, crew, and their activities.

- Many past activities were initiated from the ground level, but starting at the top with conversations with ship owners and operators will likely be most productive.
- Clear communication is essential:
    - Have a single, clearly designated point of contact on each side, who will then be responsible for communicating with other members of the team.
    - Have clear communication of what is requested and expected from each side.
    - Processes for communication with the ship while in route and monitoring of their schedule are essential.
    - Ship personnel must be aware of what the instruments are measuring, what actions might impact them, and any

safety concerns or potential for interference.

- Showing gratitude, humility, and respect to the shipping company, captain, and crew is important.
- The pilot program should consider ways to reciprocate by asking how the shipping company might use the relationship to enhance their sustainability goals as well as with publicity, advertising, an annual report, or a sustainability report they can use for their board or investors.
- A scientist occasionally riding on the ship may enhance relations.
- The possibility of training ship personnel to do some maintenance (for compensation), such as cleaning optical ports or filling fluids, would have to be cleared with the captain and shipping company, and would require retraining as crew rotate on and off the ship.

Time/Scheduling and Installation/Maintenance in Port

The instruments or instrument packages must be installed while in port or in dry dock. The amount of time that ships spend in port varies, with liner ships generally spending as little time as possible while bulk vessels may be in port for weeks. Most ships have cranes and forklifts to load cargo and supplies, thus physically getting instruments or instrument packages on the ship might not be an issue, although the time allotted for installation and positioning may be (some port calls are longer than others, and longer stays could be targeted for maintenance). Accessibility of the ships in various ports might also be a concern.

- Ships spend longer in dry dock, so initial installation during that time may be an option; however, dry-docking often occurs in foreign locations, happens infrequently (~every 3-5 years), and may have additional expense and time constraints.
- Modular instrument containers that would allow all instruments to be switched out as a package in port would be valuable and would also allow the entire instrument package to be removed for maintenance or calibration. Duplicate modules would allow uninterrupted measurements while the other module was undergoing calibration/maintenance.
- Some ships spend more time in port than others, depending on the type and route. For instance, the cargo container ship used for the ARM facility's MAGIC field campaign spent one to two days in port each week, which allowed time for instrument observation and maintenance.
- For ships that follow regular routes between two ports, it may be possible to hire someone local at one of the port locations for basic maintenance, cursory observations, downloading data, preservation/shipment of samples, cleaning of optics, etc.

Instrument Location

Placement of the instruments for accurate measurements is critical, as is ensuring that the instruments do not interfere with ship and crew operations. Instruments must be near power and must be grounded. It is also important that the instruments are not perturbed by ship or crew operations, including stack exhaust, galley exhaust, smoking, or shading or flow perturbations induced by ship infrastructure.

- Ideal locations for most instruments are probably near the bow, far upwind of the stack, and as high as possible, possibly on top of the bridge or on a bow mast. Ideally, instruments will not be near locations of ship activities, foot traffic, or smoking, but this may be difficult to ensure. Careful placement will be a better option than asking the ship to create a non-smoking area near aerosol inlets, which may interfere with crew operations or leisure. Locations with clear views of the sky are a requirement for some instruments.

- The degree to which instrument placement would allow measurements that will enable the desired science may be an important factor in developing a partnership with a particular ship or shipping company.
- Preliminary visits to the ship and communication with ship officers and crew about possible instrument location is essential.
- Some measurements may benefit from the installation of duplicate instruments in multiple locations (e.g., an optical package could be deployed on each side of the ship to ensure that one unit will always be unaffected by shading from the ship).
- Computational fluid dynamics (CFD) modeling can provide crucial information for the best location of instruments by analyzing the airflow around the ship. Commercially available CFD software can efficiently conduct simulations for different wind directions and speeds and ship geometry.

Instrument Hardening and Maintenance for Marine Environments

The shipboard marine environment is hard on instruments because of extreme conditions of temperature, relative humidity, and precipitation; corrosion, especially of cables and electronics, from sea spray; and vibration. Thus, all instruments and instrument packages must be hardened to prevent instrument failure and to ensure successful operations and data collection under marine conditions. Maintenance of instrumentation is critical for high-quality data and may require considerable effort in a marine environment – optics may become coated with sea spray, inlets/orifices on some aerosol instruments can be clogged (especially if exhaust is sampled), and corrosion may be an issue. Some instruments, as currently operated, require regular replenishment of fluids. Instrument repair during the short time in port may be difficult and the likelihood that an underway technician would have enough spare parts and knowledge to repair all the instruments in the suite deployed is unlikely. Factors that should be considered include:

- Instruments and instrument packages must be sealed against the elements (i.e., to international standards for electrical enclosures in extreme environments) and, for some deployments/instruments, maintained in a temperature-controlled environment so that the instruments do not freeze or overheat. Contingency planning for failure of climate-controlled conditions is also needed.
- Instruments must be installed so that mountings and connections do not work loose from vibration or sudden motion from wave impact.
- It is crucial that all instruments can undergo a loss of power or a rapid controlled shutdown (in a restricted military area, for instance) without damage, losing data, or losing time synchronization. Automated shutdowns would require remote communication, but it is not clear how fail-proof that option can be made. If ship personnel are required to enable shutdown, then a single point of contact is essential.
- Redundancy of critical measurements is an option, but needs to be weighed against the importance of having different measurements, cost, space, etc.
- Maintenance or repairs done underway might interfere with ship operations and would require either a trained technician or training multiple crew members (as crew members swap in and out on different legs).
- Development of automated techniques for cleaning instruments (such as water jets for optical instruments) might be helpful although this would add complexity and additional moving parts.
- Larger reservoirs of fluids required by instruments (water or butanol) might need to be provided. Crew members might be able to be trained for low-skill work such as fluid replenishment.

Power

All instruments will require access to power. While access to power would probably not be an issue for the types of instruments likely to be part of a pilot study, there are several factors to consider. One is the distance from outlets: running cables long distances can be a safety concern and can interfere with ship operations. Cleanliness of power is also a concern, as instruments and computer systems operate better with clean, consistent power. Power outages can result in instrument damage or loss of data.

- Uninterruptible power supplies (UPSs) can be employed to provide clean power and continue to provide power during outages until a safe shutdown can occur.
- All instruments should have a clean shutdown option so that they are not harmed and do not lose data or timing if a power outage occurs.
- Solar power raises concerns about reliability, sea spray coating the panels, the amount of power that can be provided, the likelihood of cloudy days, and the difficulty in orienting the panels.
- There may be safety concerns with battery power, including those used in UPSs.
- There are multiple voltage and frequency standards on ships, so a universal power box to provide standardized power to a suite of instruments would be valuable.

Ship Motion

Ship motion during measurement will introduce perturbations on the desired signals. Heaving can introduce an additional vertical velocity that will impact Doppler measurements. Pitch and roll will cause vertically pointed instruments to point away from the zenith.

- Pitch, roll, and yaw should be measured to correct the data. The ship may have some navigational data available, but reliably obtaining and converting these data to appropriate formats will probably be unfeasible. It would be preferable to have a dedicated inertial measurement unit (IMU; 3D orientation, acceleration, and for some instruments, heading) that is locally integrated and time-synchronized with the instruments deployed.
- Mechanical (active) stabilization to ensure that an instrument always points vertically may be necessary for some measurements. However, active stabilization requires additional instrumentation and moving parts and may not fully account for large heave.
- Instruments that require working fluids may be susceptible to flooding and may require hardware modifications to harden against motion.

Ship Exhaust

Exhaust from the ship stack can affect data (if background conditions are the quantities of interest), may harm instruments due to high concentrations, and can coat optics. Thus, measurements of gases or aerosols and measurements from upward-pointing instruments may be affected by ingesting ship exhaust or viewing through it.

- Placement of instruments far ahead of stack will resolve much of the concern over these issues. Additionally, when the ship is moving faster than any rearward wind the exhaust will not be an issue.
- Monitoring proxies for ship exhaust such as CO mixing ratio and/or black carbon concentration, aerosol absorption, or relative wind speed will allow determination of when ship exhaust has been sampled. It is important to note, however, that in a shipping lane, there may be high concentrations of exhaust, and it may be a challenge to determine what fraction comes from the current ship and what can be considered “background.” The ability to measure the background levels of ship exhaust in a shipping lane may be

useful for studies of aerosol-cloud interactions.

- Conditional sampling and automatic shutoff depending on measurement thresholds (e.g., CO mixing ratio) are possible, but based on experience with past campaigns such as the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC), these are difficult to automate reliably.
- Some aerosol instruments, including filter samplers, should be turned off in and near ports to eliminate clogging of instruments or sampling port emissions, although the exhaust from the ship on which the instruments reside, or other ships, could still coat optics.
- Direct monitoring of the ship exhaust would not be feasible as a routine measurement, as it would require instrument design and placement much different from those in normal operation and there may be sensitivity from shipping companies about gathering these data. However, some shipping companies measure their own ship exhaust and may be amenable to sharing these data. The ability to use ship exhaust data for data quality purposes and/or for science may be a factor in selecting a shipping company with which to partner.
- CFD modeling could help understand ship exhaust under different environmental and ship geometry conditions.

Data and Remote Monitoring of Instruments

Data quality is paramount, but there will necessarily be a tradeoff between data quality and the acquisition of any data from autonomous measurements at sea. Collection and integration of metadata is also crucial. Data must be transferred off the ship, quality-controlled, archived, and made available. Decisions must be made about responsibility for data ownership, quality assurance/quality control (QA/QC), distribution, archiving, and metadata. Remote monitoring of instrumentation would be useful to track the instrument status or performance, know if the data are valid, and know what instruments need maintenance or replacement when the ship comes into port.

- Deck-mounted instruments might require communication between the instrument and a logging computer located inside.
- Data transfer from the ship via satellite in real time is possible but may be costly with high data volumes. Storing data on the vessel and transferring it in port via remote communications or hand-carrying hard drives requires data storage systems large enough to contain data from the entire voyage. Port communications outside of the U.S. may provide challenges.
- Critical measurements and acceptable data quality must be discussed and evaluated for given science questions. The balance of volume of data over quality of data must be decided: for instance, is it better to have lower-quality data over vast regions of the ocean rather than higher-quality data over fewer regions? Methods to reduce individual measurement uncertainty, such as averaging, should be considered.
- Routine QA/QC is essential to ensure high-quality data. Development of automated QA/QC tools (possibly using edge computing) and low-data-volume flags or quick looks that could be sent via satellite would be valuable.
- While remote control of the instruments could be valuable, it is unlikely because of increased complexity, data volume, and personnel required. Similarly, having cameras monitor instruments might be valuable, but raises concerns about privacy and the amount of footage that would have to be examined.

- Metadata, such as when ship activities might have interfered with measurements, is important information, but often can be obtained from motion data. It is unlikely that the ship's crew can maintain such a logbook, or that it will be in a format that is easily accessible.
- Calibration and uncertainty of sensors and instruments are necessary metadata that must be communicated with the data.
- Using community standards for formats and metadata will be key in making data accessible to the broader community. Creation of merged data sets, including combining with satellite data, would be valuable.

Atmospheric instrumentation was installed on the container ship, Horizon Spirit, during the MAGIC campaign. Image courtesy of Horizon Lines.

Legal Concerns Specific to Ocean Observations and/or Commercial Vessels

The activities associated with a pilot program may occur on ships that are not U.S. flagged and will travel in waters and arrive in ports that are under the jurisdiction of different countries. International and individual country water laws will apply in those cases, and it is likely that many situations must be handled on a case-by-case basis. Additionally, many of the crew may be non-U.S. citizens, and might not be able to speak or read English fluently. Specific concerns noted are:

- Transportation of passengers or goods between U.S. ports is only possible on Jones Act ships (which must be U.S.-owned and crewed).

- Knowledge of the Export Administration Regulations, which govern the export and re-export of some commodities, software, and technology, will be necessary. Items restricted by the International Trade in Arms Regulations must have increased security while on board, and some items might require an Export Control Classification Number.
- There will be insurance concerns for any scientists/technicians who are on board.
- Removing or installing instrumentation at a port may result in it being considered an import or export, making it subject to customs fees. Careful planning and a good relationship with the ship operator may prevent these situations.
- There may be legal restrictions on taking physical samples in some countries and, more generally, there may be issues with sampling in Exclusive Economic Zones (EEZs). Permission to gather data in these regions might require State Department assistance, and it can be challenging if the route changes unexpectedly.
- Measurements of pollutant emissions might have specific regulatory concerns.
- Hazardous materials must follow all regulations, be self-contained, and not interfere with the ship's International Maritime Dangerous Goods code or any of its certifications.
- Any modifications to the ship must be approved by regulatory agencies such as the American Bureau of Shipping or comparable agencies in other countries.

Some of these issues may be alleviated by using standard ship processes and vendors whenever possible, being aware of international laws (such as World Meteorological Organization [WMO] agreements allowing some measurements in any waters), determining which instruments require approval in waters or airspaces of other countries, and involving the State Department for agreements regarding making measurements when in EEZs. Other programs, such as Science RoCS and NOAA, may provide useful examples for navigating these issues.

Hazards/Risks

Some materials necessary for the installation, operation, and maintenance of instruments may be classified as hazardous. It will be important to develop a careful inventory of any potential hazards and risks and how they relate to relevant international laws and to the laws of the countries in which the ship sails and docks.

- Potential hazardous materials include radioactive or ionization sources for aerosol instruments, chemicals such as butanol (used in aerosol instruments) or $HgCl_2$ (added to water samples to prevent microbial growth), gas cylinders, batteries, and nanoplastics in calibration materials. Ships must report everything that goes overboard, which may impact calibration practices, such as use of polystyrene latex spheres for aerosol calibration. In some cases, hazardous materials can be handled in port rather than on the ship, such as dry ice or liquid nitrogen for cryo-shipping of samples for ice nucleating particle (INP) characterization.
- Active remote-sensing instruments, such as lasers, lidars, and radars, may create hazards due to eye safety or electromagnetic radiation. Certain lidar wavelengths cannot be used in foreign ports and all such instruments should be turned off when coming into ports, passing under bridges, near airports, near military installations, or in restricted waters. It will be important to develop simple and failsafe shutdown plans for these instruments that do not rely on communications from shore or personnel on the ship and that prevent damage to instruments and loss of data.
- Crew members should receive proper guidance and training for safely working on or around instrumentation.

- Cybersecurity protocols must be implemented for ship-to-satellite, ship-to-shore, or port-to-data-archive communications for data transfer and remote instrument monitoring.
- There is a risk of loss of instrumentation through theft or accidental damage during shipping operations.
- Potential risks associated with piracy or military threats should be considered when selecting routes.

Instrumentation/Data

The goal of this session was to understand the feasibility and challenges of deploying given instrument types on commercial ships. Expected outcomes were ranking of instrumentation in terms of feasibility/readiness for autonomous deployment on commercial ships and identification of development needs to make instruments more feasible for deployment. Plenary presentations were provided on current shipborne aerosol measurement capabilities by Trish Quinn (NOAA Pacific Marine Environmental Laboratory [PMEL]) and on current shipborne and buoy-borne atmospheric state measurement capabilities by Raghu Krishnamurthy (PNNL). These presentations provided a background for the following breakout session discussions. Following the plenary sessions, attendees self-selected attendance at one of two concurrent breakout sessions, one of which focused on measurements of aerosols, greenhouse gases, and ocean properties, and the other of which focused on measurements of clouds, radiation, and atmospheric state.

Each of the concurrent sessions started with a preliminary list of measurements compiled from responses to the pre-workshop questions and each concluded with a ranking exercise. Participants were asked to 1) rank the scientific priority and 2) rank the feasibility for unattended/autonomous operation on commercial ships for each of the measurements. Participants were provided with four categorical options: “low,” “medium,” “high,” and “unable to judge.” The survey was filled out at the end of breakout sessions and then repeated on Day 3 of the workshop to allow participants to reflect on the discussion from the preceding plenary and breakout sessions.

Measurement of Aerosols, Greenhouse Gases, and Ocean Properties

The first session focused on aerosol, ocean, and greenhouse gas measurements. Open discussion was used to refine the preliminary list for completeness. The remainder of the session was used to solicit feedback from the session attendees regarding 1) the details of the measurement, 2) the availability of commercial instruments, 3) maintenance needs during voyage/at port, 4) data needs, 5) challenges associated with the measurement, and 6) current limitations for unattended or minimally attended shipborne operations. These discussions are summarized below and more details on each measurement are presented in Appendix C (Table 2).

Figure 1 summarizes a ranking by the workshop participants that attempts to assign the scientific priority and feasibility to certain measurement types.

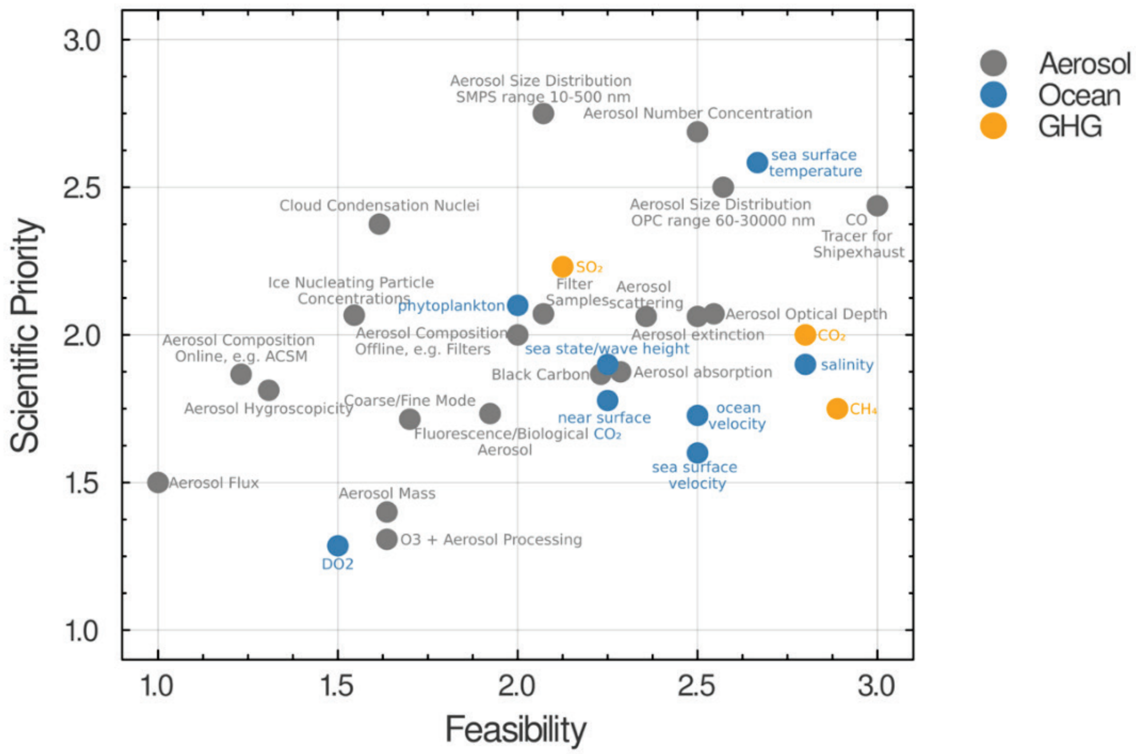


***Figure 1**. Summary of feasibility and scientific priority for the aerosol, ocean, and greenhouse gasses measurements. Rankings were determined based on voting by workshop participants. Larger numbers indicate higher feasibility and higher priority.*

Most of the discussion focused on aerosol instrumentation. Ocean measurements were less discussed, partly because significant expertise and infrastructure is already in place to measure ocean properties on commercial vessels (e.g., Science RoCS and NOAA Ship of Opportunity Program). Greenhouse gas measurements were thought to be generally feasible using commercially available gas analyzers. Thus, the remainder of this summary focuses on aerosol instrumentation.

To further simplify the discussion, instruments were divided into two categories: “feasible” measurements and “moderately feasible” measurements. Feasible measurements are defined as measurements that can use commercially available instruments with small modifications. Moderately feasible measurements are those that require significant hardening of instruments for long-term unattended deployment at sea.

Measurements identified in the feasible category are aerosol size distribution with optical particle counters (generally diameters > 100 nm), total aerosol number concentration (diameters > 10 nm), aerosol scattering, aerosol absorption, aerosol extinction, and cloud-base height and aerosol profiles from a ceilometer.

Most aerosol instrumentation will require integration into a pod or container. Critical requirements for the pod include the design of an inlet system that preconditions the sample in various ways, such as providing constant upper size cuts; constant, low, and known sample relative humidity; and constant and known transmission efficiencies as a function of particle size. Inlet characterization is particularly important for larger particle sizes and may need to consider potential effects of ship superstructure on wind flow. Inlets should be tested under laboratory and land-based conditions prior to deployment on a vessel. However, it is noted that characterizing transmission efficiencies of large particles remains difficult due to a lack of known or readily available standards for calibration and no accepted way of validating any results. CFD simulations can be used but may be expensive. The pod will require temperature control to ensure that instruments operate within specifications. A shared and networked data acquisition system will be required to log the data and remotely control the instruments. Even feasible measurements/instrumentation will require some engineering effort to ensure satisfactory operation under heavy seas, implementation of remote instrument control, automated recovery on power failure, and improved monitoring of instrument performance (such as laser power, air flow rates, or potentially automated calibration tests for overall instrument performance). Measurement of total particle concentration requires working fluids that need to be refilled. Exhaust air may need to be treated and vented. Corrosion and plugging of lines are general concerns for all in situ aerosol samplers. An additional concern is contamination by ship exhaust. The latter can be addressed by measuring CO or using total particle concentration to screen out periods of sampling ship exhaust.

Measurements identified in the moderately feasible and high-priority category are turbulence updraft and backscatter profiles from Doppler lidar, electric mobility-based size distribution (10-500 nm), and filter samples for ice nucleating particle concentration and aerosol composition. Deploying a Doppler lidar successfully will require the design of a motion stabilizing platform. Deploying instruments to measure mobility-based size distribution will require hardening to prevent arcing, cleaning procedures of the interior of the column, improved flow control, and software development to ensure unattended/remote operation. Furthermore, the technique generally relies on particle counters with liquid reservoirs and aerosol charging by radioactive sources. Both lidar and mobility measurements will require development of safety protocols for the crew and research of regulatory compliance for operating the instruments worldwide. Successful filter sampling will require conditional sampling by wind sector, possible real-time screening of periods with ship exhaust, improved samplers to rotate filters, and protocols to store, retrieve, and process the filters. Although plausible solutions exist to overcome the raised concerns, it was clear from the discussion that these instruments/techniques require hardening and engineering effort beyond the issues raised for the “feasible” instruments.

In general, the aerosol datastreams will require thorough QA/QC pipelines. Some QA/QC can be automated, but those procedures need to be developed. Datastreams will require varying amounts of post-processing, perhaps similar to that for value-added products within ARM, prior to release to the public. Deployment of filter samplers will require post-processing of samples, which requires personnel and time prior to data release. External data sets, including satellite data, may need to be leveraged to realize science goals based on the set of deployed instrumentation. Infrastructure that already exists in ARM to handle data ingestion, curation, distribution, and archiving may serve as a guide to establishing protocols. Analysis of the collected data is likely complex and will require dedicated funding streams to realize science goals.

Measurements of Clouds, Radiation, and Atmospheric State

The second instrumentation session focused on discussion of clouds, radiation, and atmospheric state measurements. It is important to balance scientific priority with feasibility for unattended deployment on a ship. As in the concurrent session, a list of potential instruments was identified from the pre-workshop responses, and participants were asked to rank them in terms of scientific value and feasibility for unattended shipborne observations.

The results of this survey, shown in Figure 2, indicate that a notable set of measurements can provide high scientific value and are feasible for unattended operations. Measured quantities in this set are surface meteorology, solar radiation, and cloud-base heights. It is expected that all measurements will require ship position and navigation information. Additionally, many measurements will require co-located IMU to measure ship motion (roll, pitch, heave, etc.) to enable motion correction and for quality control purposes. While communications could be limited, it is important to collect all available diagnostic data from any system deployed (voltages, temperatures, etc.).

Measurements that were high scientific priority but considered moderately feasible, as they would need some development or instrument hardening for unattended marine deployments, were planetary boundary-layer (PBL) height and liquid water path from microwave radiometers. While PBL height can be retrieved from most of the backscatter lidar systems (including the feasible-to-deploy ceilometer), lidar-based PBL heights have greater uncertainty under marine conditions (Zhang et al. 2022). Concerns raised about microwave radiometer feasibility were the need for liquid nitrogen calibration, the requirement for window cleaning and blower fans, and the possibility of window covers being punctured.

Other measurements that were listed as feasible, but with somewhat lower scientific priority, were observation of sky condition from sky imagers or cameras, surface fluxes, turbulence and updraft retrievals from Doppler lidar, and cloud-base temperature from infrared thermometers. Deployment of sky imagers would likely require software development, perhaps edge computing, to retrieve parameters of interest from a moving ship. Direct measurements of surface fluxes are possible with systems such as those used by NOAA mounted on a bow mast. Bulk fluxes of heat and moisture (which might be suitable to address some science questions) could be derived with standard algorithms (Fairall et al. 2003) using measurements from the instrumentation deployed for the surface meteorological system, although this requires the met system to be optimally located and flow distortions considered. These algorithms are regularly applied to observations from the Shipboard Automated Meteorological and Oceanographic System initiative (Smith et al. 2016). Deployment of Doppler lidars for turbulence and updraft velocity retrievals would require further marine hardening and automated window cleaning systems. A co-located IMU would be required to correct for ship motion. A stabilized platform would be needed to measure instantaneous wind profiles to address some science questions.

The remaining measurements, such as precipitation, cloud optical depth, and others shown in Figure 2 have lower feasibility for deployment and were ranked of lower scientific value by workshop participants. These measurements would provide value for certain scientific questions, but would need investments (sometimes significant) to make them robust for unattended marine observations.

General challenges that many instruments will encounter include the deterrence of birds, potential icing, and the robustness of marine cables. Additionally, it will be important to have the ability to power cycle instruments remotely and for the system to automatically turn off data collections depending on the location. For example, if there are data embargo zones around countries, the system will have to automatically stop data collections prior to reaching that zone. Any scanning system, such as lidar, will need to have failsafe protections to ensure that the laser does not scan the ship or any other unintended areas in the event of a failure.

Appendix D provides more detail on the instruments discussed during this breakout session.

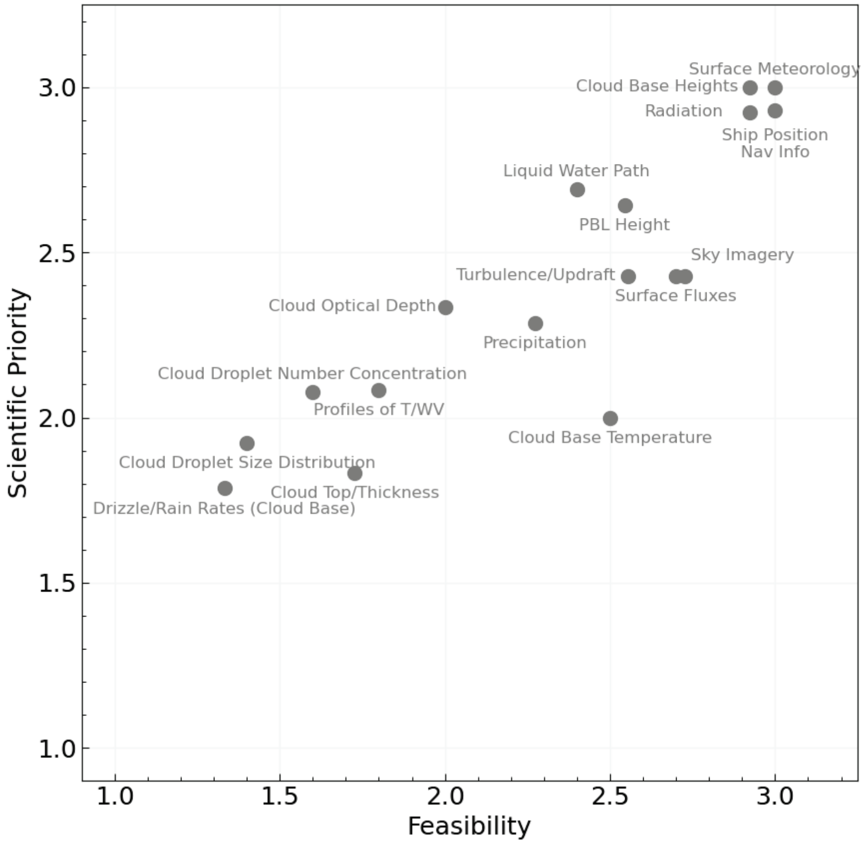


***Figure 2**. Clouds, radiation, and atmosphere measurements ranked by scientific priority and feasibility. Rankings were determined based on voting by workshop participants. Larger numbers indicate higher feasibility and higher scientific priority.*

Science Topics

Introduction

Following the discussion of the logistical challenges and feasibility of making measurements on commercial ships, the second day of the workshop was dedicated to discussing high-priority BER-relevant science questions that might be well suited to an initial pilot project. Before the workshop, the organizers analyzed and summarized the pre-workshop responses and grouped them into categories. These were shared with session facilitators who were asked to develop several science questions for discussion based on both the workshop input and their own scientific expertise. To assist the facilitators, each breakout session was provided a worksheet that included a set of questions for each identified science topic:

- Why is this question critical for improving Earth system predictability and/or meeting BER scientific goals? What hypotheses could be tested? How does this question address long-standing assumptions or approximations about aerosol, cloud, and/or radiation properties and/or processes?
- Why is it suited to opportunistic measurements?
- Which measurements would be necessary?
- Which region(s)/shipping lane(s) would be appropriate?
- What type of measurement statistics and/or length of measurement record would be necessary?
- Are there particular challenges to address or necessary resources?

The following sections summarize the breakout session discussions. The amount of discussion of the science question and the sub-questions that were addressed varied among the sessions. In general, higher perceptions of measurement feasibility for a particular science question led to discussion of more of the sub-questions and lower perceptions of measurement feasibility led to more discussion of the measurements themselves.

Session 1a – Boundary-Layer Structure

The session focused on three science questions related to boundary-layer processes occurring at 2-20 km spatial scales that could be addressed using the data collected from ships of opportunity. These questions align with BER scientific goals, and due to the lack of existing data over coastal regions and open oceans, are suitable to be addressed from opportunistic measurements. Each of the questions below relates boundary-layer processes to clouds and precipitation: 1) the degree to which the boundary layer is mixed or stratified, 2) mesoscale convective organization, and 3) processes related to ship tracks.

Hypotheses related to these questions could be tested through the analysis of data collected by basic instrumentation packages consisting of 1) surface meteorological stations, 2) ceilometers, 3) Doppler lidars, 4) microwave radiometers, 5) sky imagers, 6) broadband radiometers for measuring downwelling longwave and shortwave radiation, and 7) instruments measuring surface aerosol size distributions. Opportunistic observations made for six months to a year over eastern subtropical oceans that have high coverage of warm low clouds would be ideal for addressing these questions. Key challenges are modifying the instruments to make observations from a moving platform (e.g., sky imager), correcting turbulence measurements for ship motion, and co-locating the collected data with those from polar orbiting and geostationary satellites (see also Session 2a).

Science Question 1 – How do boundary-layer thermodynamic and dynamic decoupling vary with cloud, precipitation, and surface meteorological fields?

A boundary layer is considered decoupled when the lifting condensation level calculated from surface meteorological measurements differs from the cloud-base height. It is essential for Earth system models to simulate boundary-layer decoupling as it is the first step during the transition from a stratocumulus cloud regime to a cumulus cloud regime that is observed over eastern subtropical oceans. However, a range of models struggle to accurately simulate boundary-layer decoupling partly due to an inadequate understanding of the pertinent factors such as precipitation, surface fluxes, wind shear, and boundary-layer radiative cooling.

In situ data are limited over oceans, and large data sets from ships of opportunity will allow testing model parameterizations of boundary-layer decoupling under different large-scale forcing, cloud, and precipitation conditions. A large data set (3-6-month minimum; multiple years preferred) would provide enough samples to classify observations by large-scale forcing (i.e., inversion strength or advection) to examine how the decoupling index depends on surface and cloud properties. Climate models also struggle with simulating the effects of continents on coastal stratocumulus clouds, leading to low biases in near-shore cloud amounts. More data on near-shore atmospheric and cloud conditions could help identify factors contributing to these biases.

Observations that would address these questions are surface meteorology (to calculate the lifting condensation level) and ceilometer-measured cloud-base height. The difference between these two values can be used to diagnose the degree of decoupling (Jones et al. 2011). Turbulence profiles in the boundary layer from Doppler lidars and rain rate from dual wavelength lidars would also be useful. A stabilized platform for the Doppler lidar would reduce the uncertainty in the derived turbulence parameters and may allow calculation of cloud-base updraft in well-mixed conditions. Combining the lidar measurements with surface aerosol measurements and a cloud parcel model may allow calculation of cloud-base droplet number concentration.

Ideal regions for observations are open-ocean regions of stratocumulus-to-cumulus transition in the Northeast Pacific, but any routes with warm low clouds would be useful for addressing the question. Data collected over shipping lanes along coastlines would be useful for addressing science questions related to continental effects on low clouds.

Science Question 2 – How do boundary-layer conditions and surface fluxes influence moisture aggregation at the mesoscale and what are the resulting effects on cloud and precipitation fields?

Understanding the factors that control mesoscale aggregation of moisture and cloud field organization affects marine cloud reflectivity and precipitation and understanding these processes could lead to improved representation in climate models. Observations of wind convergence around dry and moist patches, statistics of the diurnal cycle of mesoscale cloud organizations over the open ocean, and the impact of sea surface temperature (SST) and SST gradients on mesoscale cloud organization would provide important information to constrain and improve models and are not available from satellite-derived global data products. Gradients in water vapor, clouds, and precipitation can exist within a climate model grid cell, which has implications for cloud overlap and radiation, as well as non-linear microphysical processes like autoconversion.

Mesoscale shallow convection often manifests as cloud organization patterns. There is a long history of study of closed- and open-cellular convection, and pockets of open cells, all of which fall under a broader class of actinoform clouds that manifest rich patterning of different kinds (Garay et al. 2004). The relationship between actinoform patterns and marine boundary-layer processes is relatively unexplored and would be valuable. More recently, organization patterns have also been a subject of study in the Atlantic Ocean. Expanding studies of organization to the Gulf Stream or loop currents that affect surface fluxes, oceanic SST gradients that cause cloud transitions, and/or the transition from the inter-tropical convergence zone to suppressed tropical regimes would also be worthwhile. Ship-based observations to complement recent airborne campaigns (such as NASA's Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment [ACTIVATE] campaign) would also be useful.

Developing contour maps of frequency of occurrence and optical properties, and general quantification of cloud-field organization, would be useful to address outstanding questions about the radiative effect of different mesoscale cloud organizations that are subgrid in Earth system models, and the role that water vapor and precipitation play in determining these mesoscale cloud organizations.

Measurements and instruments needed to address these questions are surface meteorology, vertical backscatter profiles from ceilometer, ship navigation information, downwelling broadband shortwave and longwave fluxes, cloud fraction/morphology determined from a sky imager, turbulence profiles from Doppler lidar, integrated water vapor and liquid water path from a microwave radiometer, and surface rain rate from in situ sensors. Combining the shipborne observations with geostationary satellite observations would provide information on the large-scale cloud organization but will require software to match satellite and shipborne observations. MAGIC observations have shown surface precipitation to be difficult to measure on ships, so it will be useful to have multiple sensors. Newer optical sensors are less sensitive to wind and can be corrected if a sonic anemometer is nearby.

Addressing these science questions will require measurement records of at least several months to a year in a particular regime. Depending on ship routes, a single ship may pass through multiple regimes and seasonal weather patterns. While this provides the opportunity to address multiple different science questions, it may take longer to build a statistically significant data set for a particular regime.

Science Question 3 – What are the gradients of boundary-layer dynamic, thermodynamic, cloud, and precipitation structure within and around ship tracks and shipping lanes?

A fundamental challenge in Earth system models is how well they represent impacts on cloud albedo and precipitation associated with changes in aerosol concentration. Cloud brightening around ship tracks has been used as a proxy for the first aerosol indirect effect, and observations could be used to test whether there is cloud dimming around ship tracks or suppression of precipitation within them (Diamond et al. 2020). An important question is what factors besides aerosol and background meteorology enhance or diminish the cloud brightening in shipping lanes.

Targeted shipborne field campaigns are often conducted in remote regions away from ship traffic, but commercial ships, by definition, will be traveling in shipping lanes that will provide frequent opportunities for observations of tracks from other ships. An ideal route for addressing Science Question 3 is one that transits across shipping lanes. Multiple transects through ship tracks in different stages of their life cycle would be very useful; however, detailed measurements along even one ship track would be useful due to the dearth of data. While quantifying the age of ship tracks is often difficult, geostationary satellites can provide daytime information in order to geolocate recent tracks; in addition, data archives within the Bureau of Ocean Energy Management, NOAA, and the Coast Guard contain relevant information such as ship location, speed, and density of commercial shipping (https://marinecadastre.gov/ais/). Despite this, a very large percentage of ship tracks likely go undetected, as there are on the order of 100,000 ships in the global fleet, and yet studies of ship tracks tend to identify only hundreds to thousands of tracks per year (Christensen et al. 2022). Hence, as visible ship tracks are made only 1% of the time, it may take time to gather enough samples needed to analyze conditions under which visible ship tracks do and do not form. Another region that would allow addressing this question is the subtropical oceans because of the prevalence of low clouds susceptible to aerosol changes.

Addressing this science question would require additional measurements beyond those necessary for the first two questions, such as aerosol size distribution (Aitken and accumulation mode), trace gas measurements of CO and NOx to identify clean versus

perturbed air masses, cloud optical depth, cloud boundaries, liquid water path, and boundary-layer turbulence. Additional information about background aerosol fields (possibly from satellites) would be useful to understand the impacts of aerosol amount on cloud brightening.

Session 1b – Aerosol Characterization, Sources, and Transit

The breakout on aerosol characterization, sources, and transit discussed science questions that could be addressed centered around four science themes: 1) characterizing marine aerosol, 2) quantifying contributions from transported aerosol, 3) determining the cloud-formation potential of marine aerosol, and 4) quantifying marine aerosol cycles and environmental trends. The focus of the discussion was on direct aerosol measurements to improve understanding of aerosol processes in the marine environment with an emphasis on discerning different sources of particles, e.g., natural marine, continental, coastal, or ship-derived.

These questions were viewed to be well suited to opportunistic measurements because of the dearth of in situ aerosol measurements over the ocean. Since continental aerosol properties and processes are different than those in the marine boundary layer, measurements of continental aerosols cannot simply be extrapolated over marine surfaces. Therefore, oceanic measurements are needed to address BER scientific goals of improving understanding and model representation of marine aerosol processes and their interactions with clouds. Much of the discussion focused on which measurements would be feasible to conduct autonomously. Simplified plans with a meteorology sensor and measurement of particle number or mass concentration were discussed, but participants felt these would have less scientific impact than if it were possible to measure aerosol size distributions and chemistry using offline and/or online techniques, e.g., filter sampling, aerosol mass spectrometry, etc.

Many of these measurements would likely require a specialized aerosol inlet, as discussed above, to enable high data quality. More information about measurement needs discussed in this session can be found in Table 1. Scientific output could also be increased by combining in situ aerosol measurements with passive and remote-sensing techniques as well as oceanographic measurements when possible. However, since most space-based remote-sensing techniques cannot see below the cloud deck, in situ aerosol measurements remain critical to improve our understanding of marine aerosol characterization, sources, and transit. Furthermore, since aerosol processes are important determinants of cloud formation, they can result in large impacts on surface radiative budgets and the water cycle and, as a result, warrant increased observations that could be provided using ships of opportunity.

Science Question 1 – What are the dominant sources, sinks, life cycles, processes, properties, and quantities of aerosol within the marine boundary layer?

There are very few in situ measurements of aerosols over open ocean regions. Due to this lack of measurements and noting the differences between marine and continental aerosol properties and processes, global Earth system models are poorly constrained over the dominant surface type on Earth, i.e., the sea surface. Direct measurements of marine aerosol properties are needed to understand marine aerosol processes and their interactions with marine clouds. Measurements from ships of opportunity would provide context about the representativeness of coastal measurements for understanding open-ocean marine aerosol. Direct measurements would also help address the relative lack of satellite retrievals of aerosols in the marine boundary layer.

Sub-questions:

1. Is free tropospheric entrainment a significant source of aerosol in the marine boundary layer over remote areas?
2. What regions might be aerosol-limited for cloud and precipitation formation?
3. To what extent is cloud processing an important source of various types of organic substances in marine aerosols?
4. What are the primary processes controlling wet scavenging of aerosol in marine regions?
5. How well do model-predicted speciated aerosol mass concentrations over the remote ocean agree with in situ measurements? Where do measured concentrations indicate gaps in our knowledge of aerosol processing within the marine boundary layer?

Marine clouds as seen from Graciosa Island in the Azores, home to ARM's Eastern North Atlantic (ENA) atmospheric observatory. Photo courtesy of ARM.

The current paucity of aerosol measurements over the open ocean necessitates that any measurements will be highly useful to the community. Opportunistic measurements will help build a climatology of marine aerosol over remote ocean locations that are not easily accessible. Measurements at different distances from the coast will be possible, and the repeatability of commercial routes lends itself to developing statistically relevant data sets.

Surveying global properties in different seasons (i.e., via a route that circles the globe 3x per year) would be useful. Developing climatologies over open-ocean regions would be beneficial, but these should be compared to smaller regional studies where repeated tracks are possible. Coastal areas near land-based monitoring stations with historical data or regions with recent aircraft or ship-based field campaigns would also provide useful information. Areas with rich historical data sets include coastal California, paths between the U.S. and Europe that would allow comparison with observations from the Mace Head Atmospheric Research Station in Ireland and the ARM Eastern North Atlantic (ENA) site in the Azores, and tracks from the U.S. to Australia/New Zealand to compare with recent Southern Ocean campaigns in different seasons. Marine areas with more complicated dynamics than classic stratocumulus regions (such as Southeast Asia and the Northwest Atlantic) would allow investigation of topics such as aerosol-cloud interactions with which models struggle. Some repetition would be needed to characterize particular regions, with ideal data sets including on the order of 50+ measurements for statistically resolving different back trajectories.

The strength of commercial shipborne measurements is that they provide statistically meaningful measurements over the remote oceans. A potential weakness is that these statistics may be biased depending on where the sampling occurs. Consideration should be given to the potential bias that sampling within shipping lanes might introduce.

Science Question 2 – What fraction of aerosol in the marine boundary layer is associated with transported continental, coastal, and/or shipping sources?

The properties of transported aerosol in the marine boundary layer will generally be different from those of aerosol from natural marine sources, and likely different from those of aerosol transported from land. Knowledge of marine aerosol properties and how much aerosol is produced locally by natural or anthropogenic sources instead of being transported from continental or coastal sources is necessary to constrain and evaluate aerosol and dynamical processes over marine regions in Earth system models. Because of their different properties, locally produced and transported aerosol may have different impacts on radiation budgets, atmospheric chemistry, and cloud formation. Direct measurement and quantification of transported sources would help understand the impact of changes in aerosol source regions (i.e., due to changes in drought, wildfire, or industrial pollution) in future climate scenarios. Beyond BER science, answers to this question would help with understanding implications for health and regulatory actions if dominant sources are identified.

Sub-questions:

1. What are the relative contributions of anthropogenic and marine aerosols in the marine boundary layer?
2. What is the background direct aerosol radiative forcing under conditions without anthropogenic emissions?
3. How do anthropogenic emissions from continental, coastal, and ship-based sources influence direct radiative forcing?

Science Question 3 – What are the relative contributions of cloud-forming aerosol from local/regional marine sources and from transported terrestrial sources over the open ocean?

As discussed above, aerosols produced from local/regional marine sources and those transported from terrestrial sources may have different properties and, therefore, different potential to serve as cloud condensation nuclei or ice nucleating particles. Measurements from ships of opportunity in different regions would make it possible to study regional differences in which aerosols act as cloud condensation nuclei (CCN) and how those differences impact cloud and precipitation processes.

Science Question 4 – What are the seasonal and diurnal cycles of marine aerosol and how do they vary with environmental conditions, e.g., clear sky versus cloudy, before and after precipitation, etc.?

Diurnal cycles have been observed for sea salt production (Flores et al. 2021), but the magnitude of the diurnal cycle varied with ocean region. More observations are needed to understand the diurnal cycle of marine aerosol concentrations for different regions, e.g., coastal, shipping lanes, remote open ocean, etc. Opportunistic measurements from commercial ships would enable sampling during different seasons and marine environments with repeated coverage to understand variability and the overall representativeness of the data. Sampling repeated routes over multiple years would allow interannual variability and seasonality to be assessed. Most previous marine field campaigns are limited in their ability to broadly link to biology and ecosystem science, but sampling over repeated transects, as could be done here, would provide this ability. This science question may also be best suited for deployments that include supporting oceanographic data such as the type that are collected by Science RoCS.

Measurements to address this question are summarized here and the required instruments are listed in Table 1. Critical measurements are size distributions covering freshly formed particles through the accumulation mode, online and filter collection for chemical composition, and surface meteorology measurements that include precipitation. While discussion was limited, participants noted that for cold clouds, ice nucleating particle measurements would also be critical. Additional measurements of value include cloud activation potential, supermicron size distributions, total number concentrations, and total sky imaging.

***Table 1**. Instrument needs for breakout sessions 1b, 2b, and 3b.C=Critical; I=Important; N=Nice to have. (DMA – differential mobility analyzer; CPC – condensation particle counter; ACSM – aerosol chemical speciation monitor; OPC – optical particle counter; HTDMA – humidified tandem differential mobility analyzer; APS – aerodynamic particle sizer; CCN – cloud condensation nuclei). Note: All topics require surface meteorological measurements and position information. Filter*-Submicron filters for offline analysis of refractory components. Breakout sessions primarily discussed warm clouds; for cold clouds, ice nucleating particle (INP) measurements would also be critical.*

Science Topic	**DMA-CPC**	**ACSM**	**Filter***	**CCN**	**APS**	**HTDMA**	**OPC**	**Scat/Ext /Abs**
1b. Characterizing Marine Aerosol	***C***	***I***	***C***	***N***	***N***			
1b. Transported Aerosol Contributions	***C***	***C***	***C***		***N***			
1b. Cloud Formation Potential of Marine Aerosol	***C***	***I***	***N***	***I***		***N***		
1b. Marine Aerosol Cycles and Environmental Trends	***C***	***C***	***C***	***N***	***N***	***N***	***N***	
2b. New Particle Formation	***Nano***						***N***	
2b. Sea Spray Aerosol	***I***		***I***	***N***			***C***	
2b. Particle Growth	***C***			***N***				
2b. Impacts of Clouds on Particles	***C***	***I***	***N***	***I***		***N***		
3b. Cloud Processing of Aerosols	***C***	***N***	***N***	***N***		***N***		
3b. Closure of Aerosol Particle Activation	***C***	***I***	***N***	***I***		***N***		
3b. Effective Cloud Supersaturation	***C***	***I***	***N***	***I***		***N***		
3b. Aerosol-Controlled Supersaturation	***C***	***I***	***N***	***N***		***N***		
3b. Cold-Cloud Conditions	***C***	***N***	***I***		***I***		***C***	

Session 2a – Regional Cloud, Radiation, and Boundary-Layer Properties from Combined Ship and Satellite Measurements

Breakout 2a focused on three research questions that could be addressed by connecting shipborne measurements to satellite observations. The aims were to facilitate a greater understanding of 1) cloud adiabaticity, 2) the stratocumulus-to-cumulus transition, and 3) conditions that cause clouds to organize into different mesoscale structures. These questions are relevant to BER goals because they relate to underlying assumptions about fundamental marine cloud processes and how well they are represented in remote sensing algorithms and in Earth system models.

Participants generally agreed that basic measurements from ships of opportunity would provide valuable insights and facilitate the quantification of cloud adiabaticity, defined as the ratio of the actual liquid water path in a cloud to that predicted under the assumption of an adiabatic lapse rate. The assumption of constant cloud adiabaticity when retrieving cloud droplet number concentration from space, a key variable for studying aerosol-cloud interactions, overlooks the prevalence of sub-adiabatic clouds and poorly understood processes (e.g., cloud-top entrainment and precipitation) that lead to sub-adiabaticity. Quantification of cloud adiabaticity would largely come through combining ship-based measurements of cloud-base height, cloud-base temperature, and surface meteorology with satellite-based cloud retrievals. The problem was deemed important since there is a gap in our current understanding of adiabaticity and how it maps onto global aerosol indirect radiative forcing. Despite some uncertainties discussed on the scientific assumptions regarding the calculation of adiabaticity using this synergistic approach (e.g., not having good enough measurements of precipitation or cloud water content), it was generally agreed that this question is tractable if enough sampling of diverse meteorological conditions and cloud regimes could be undertaken.

Determining the factors controlling the stratocumulus-to-cumulus transition was felt to be a much more challenging problem than cloud adiabaticity. It would require many more observations, including some that may not be feasible (such as observations of precipitation and cloud water content from W-band radars and measurements of CCN concentration from aerosol instrumentation). Due to these challenges, it was felt that a larger-scale targeted field campaign may be better suited to address this question.

Limited discussion time was available for the third question, but participants noted that the instrumentation requirements and regions of study would be like those for the second question and would also likely benefit from a W-band radar. Finally, it was briefly mentioned that ships of opportunity may provide insight into the impacts of aerosol emissions from commercial shipping on lightning that have been observed in the Indian Ocean.

Science Question 1 – Can combining ship-based observations with satellite data reveal how cloud adiabaticity varies across marine regions? How do assumptions of cloud adiabaticity affect satellite-retrieved aerosol indirect radiative forcing estimates at global scales?

Previous studies have shown that metrics of aerosol-cloud interactions are stronger in adiabatic clouds that are coupled to surface moisture. Adiabaticity is affected by precipitation and entrainment, and models that have too much mixing by entrainment or that have too frequent precipitation produce clouds with lower adiabaticity. Ship measurements can be used to provide critical measurements of cloud-base height, cloud-base temperature, and meteorology that will allow assessment of the assumption of adiabaticity used in the satellite retrievals, reduce uncertainty in estimates of cloud droplet number concentrations from satellites, and constrain model parameterizations of entrainment and precipitation.

Observations from ships of opportunity will be important for model evaluation of cloud-base height, cloud-base temperature, and adiabaticity, but these measurements will need to be combined with cloud-top temperatures retrieved from satellites, preferably satellites in geostationary orbit where the temporal evolution of the clouds can be better collocated to the ships of opportunity. One of the main challenges is ascertaining the uncertainties invoked from assumptions used in the calculation of adiabaticity, since profiles of liquid water content will likely not be provided by the ships of opportunity. While rigorous calculations will be necessary, back-of-the-envelope calculations shared in the workshop suggest that using satellite-based cloud-top temperature to calculate in-cloud lapse rates may not introduce significantly more uncertainty than calculating the lapse rate using radiosonde measurements.

Required shipborne measurements to address this question are cloud-base height from ceilometer, cloud-base temperature from an infrared thermometer, cloud fraction from a sky imager, and surface meteorology. Integrated water vapor and liquid water path measurements from a shipborne microwave radiometer would also be valuable. A required measurement is cloud-top height/temperature from satellites. Calibrated satellite passive microwave measurements would be useful to detect precipitation and provide an additional estimate of the liquid water path. While ship-based profiles of liquid water content would be ideal, it was deemed unfeasible to have well-calibrated radar observations on ships of opportunity.

The ideal cloud conditions for addressing this question would be thick stratocumulus decks because the satellite retrieval uncertainties will be low there. Broken and/or thin clouds will be problematic for satellite retrievals. Challenges include assumptions on how rainwater path affects adiabaticity and the differences in scale between ship and satellite measurements. It may be challenging to validate results from large-scale models that assume partial cloud cover within a grid cell in the vertical with measurements from ships of opportunity.

Science Question 2 – What factors control the stratocumulus-to-cumulus transition and how do thermodynamics, aerosol, and cloud properties change during the transition?

Understanding the complexities of the stratocumulus-to-cumulus transition is crucial for refining our understanding of aerosol-cloud interactions and cloud feedbacks in the climate system. Challenges in understanding and modeling these transitions include understanding aerosol sources (such as the relative role of wind-driven emissions versus those from the free troposphere) and impacts on mesoscale structure due to wet deposition and cloud-top entrainment. Measurements from ships of opportunity across multiple stratocumulus-to-cumulus transitions could assess how well the MAGIC results compare with transitions in other meteorological regimes. Studies based on reanalysis and satellite observations (Sandu and Stevens 2011) suggest a similarity in the transition in different regions, but this has not been examined with in situ observations. Shipborne observations could also address questions on whether increases in aerosol concentration delay the transition and how surface heat fluxes and cloud-top radiative cooling impact the microphysics and cloud dynamics of the transition.

A necessary measurement to address this question is surface heat flux. More analysis would be needed to determine whether flux retrievals from bulk meteorology measurements would be sufficient or if eddy-covariance measurements would be needed; the latter would be more difficult from ships of opportunity. Additional desired measurements are sea surface temperature from downward-pointing infrared thermometer, cloud optical depth from sun photometer, boundary-layer depth, backscatter profile from ceilometer, turbulence profiles near cloud base and/or cloud-base updraft velocity from Doppler lidar or radar wind profiler, aerosol number size distribution, cloud condensation nuclei concentration, and satellite retrievals of sea surface temperature, liquid water path, and rain rate.

Measurements from the California-Hawaii route transited during MAGIC, California-New Zealand, cross-Atlantic, or cross-Indian Ocean routes would be useful, although biomass burning aerosols may impact the Eastern Atlantic route. Compositing observations of sea surface temperature and surface heat flux will assist in interpretation of results. Corrections for non-Lagrangian flow must be considered in analysis of measurements.

Science Question 3 – What are the aerosol, cloud, precipitation, turbulence, and radiation fields within and at the boundaries of different mesoscale cloud organizations?

Due to lack of time, this question was not discussed in detail. However, mesoscale organization was also discussed in Session 1a as Science Question 2.

Session 2b – Air-Sea Exchange and Boundary-Layer Aerosol Formation

This breakout session was organized around improving understanding of the dominant sources and sinks of CCN in the marine boundary layer. Some of these questions overlap with science questions raised in Sections 1b and 3b, but the focus here is on aerosol processes that occur within the marine boundary layer as they relate to CCN formation. This breakout session focused on three high-priority topics critical to predicting cloud formation and radiative impacts: 1) new particle formation, 2) sea spray aerosol, and 3) particle growth.

Topics and questions that were raised, but not discussed in detail, were: 1) aerosol sinks, specifically deposition to the ocean surface, which was highlighted in a global CCN sensitivity analysis as one of the key uncertainties in natural aerosol (Carslaw et al. 2013), 2) transported continental aerosol, specifically the contribution of aerosol entrained from the lower free troposphere to marine boundary-layer CCN, and 3) impacts of clouds on aerosol (this was extensively covered in 1b and 3b). A related topic, scavenging of vapors known to lead to particle growth by clouds, requires high-quality measurements of three-dimensional marine boundary-layer cloud fractions.

Science Question 1 – Where and when do we see evidence of newly formed particles?

Routine measurements of aerosol size distributions over the global oceans are rare, thus limiting a statistical assessment of the frequency and spatial distribution of new particle formation (NPF) events. Existing information on marine NPF events has been drawn from select field campaigns, and there is not a consensus on the importance of NPF (either within the marine boundary layer or transported from the lower free troposphere) as a source of marine boundary-layer CCN. Routine sampling of aerosol size distributions from 10-100 nm (dry diameter) would permit assessment of the frequency with which these events were observed.

Science Question 2 – What are the relative roles of sea surface temperature, wind speed, salinity, and whitecap coverage in the production of sea spray aerosol?

Sea spray aerosol contributes to marine boundary-layer CCN, scavenges new particles via coagulation, and provides a conduit for the transfer of INP and reactive halogens from the ocean to the atmosphere. Accurate sea spray aerosol source parameterizations have remained elusive. While direct eddy covariance flux measurements would be most useful to address these questions, the complexity of such measurements renders them outside the scope of this project. However, measurements of aerosol size distributions from 20-1000 nm would be very useful in evaluating existing source parameterizations and the dependency of these emissions on sea surface temperature, wind speed, salinity, and whitecap coverage. The most useful experimental tool would be a pair of size distribution measurements with combined range of 10-1000 nm (dry diameter), where the smaller size range is sampled behind an alternately dried or heated inlet to volatilize organics and sulfate. While this would not be a direct chemical measurement of sea spray aerosol, the refractory aerosol would be a good proxy for sea spray aerosol.

Science Question 3 – Under what conditions do particles grow to CCN in the marine boundary layer and what is the survival probability for very small particles?

Measurements from field campaigns have shown that newly formed particles grow in the marine boundary layer. However, the growth rates are slow (1 nm/h), making it challenging for newly formed particles to grow to CCN sizes before they are scavenged by existing aerosol particles. Direct measurements of aerosol size distributions on broad spatial and temporal scales would provide an assessment of **both** the growth rates of newly formed particles and the coagulation rates and condensation sinks. The best measurements to address these questions are the high-resolution aerosol size distributions from 10-200 nm (dry diameter).

Summary instruments: The optimal measurements to address these three goals would be a pair of mobility-based aerosol size distribution measurements that span the range 10-800 nm (dry diameter), where one differential mobility analyzer (DMA) is placed behind a heated inlet to measure refractory aerosol (a proxy for sea spray aerosol). Careful selection of the DMA columns will be required as most DMA columns do not span this entire size range. There is still a tremendous amount of science that can be done for each of these questions with a single DMA making measurements from 10-800 nm dry diameter. However, to characterize the early aerosol formation and growth period, measurements down to 1-2 nm would be ideal. As discussed earlier, inlet transmission and inlet conditioning (humidity) are likely to be as challenging as the deployment of the instruments themselves and many of the condensation particle counters (CPCs) used with the DMAs require a consumable fluid such as butanol or water.

Session 3a – Aerosol-Cloud Albedo and Precipitation Susceptibility

Two concurrent breakout sessions built upon the preceding sessions to address science questions related to how aerosols and clouds interact in the marine environment. This one focused on the sensitivity of cloud albedo and precipitation to changes in aerosols, referred to as susceptibility, which is a large source of uncertainty in climate change simulations and in Earth system predictability. Knowledge of the sensitivity of albedo to changes in atmospheric aerosols is critical for understanding aerosol radiative forcing in the current climate and for the potential for climate intervention. Characterization of susceptibility in the remote marine environment where observations are limited, and comparison with global climate models, is particularly important because clean marine clouds are thought to be highly susceptible to changes in aerosol concentration. This session focused on three topics: 1) connecting cloud susceptibility to near-surface aerosol concentrations; 2) the relationships among susceptibility, meteorological regime, and background aerosol state; and 3) the timescales of albedo and precipitation changes.

Key measurements needed to address all three science questions below are cloud optical thickness (which could be derived from downwelling surface shortwave and longwave radiation), cloud occurrence frequency (which can be made with a ceilometer), aerosol size distribution that can resolve the Hoppel minimum (i.e., covering the range 40-1000 nm), broadband downwelling shortwave and longwave radiation, liquid water path (which can be made with a microwave radiometer), and surface precipitation. Satellite measurements will be useful for addressing the precipitation susceptibility question because of the challenges of making accurate precipitation measurements from ships.

In two breakout sessions, workshop participants discussed aerosol-cloud albedo and precipitation susceptibility and how aerosols and clouds interact in the marine environment. Photo courtesy of ARM.

Science Question 1 – How do we best connect changes in cloud albedo and precipitation to variability in near-surface CCN concentrations and aerosol size distribution?

Climate models often artificially limit the minimum cloud droplet concentration because of poor current understanding of the aerosol budget in the marine boundary layer, likely introducing biases in the albedo and precipitation susceptibility of the models. Making measurements from commercial ships in a range of marine regions that might have different susceptibilities would be beneficial to progress in this area. It would be useful to compare susceptibility in shipping-heavy regions to that in pristine regions, although finding commercial ships other than cruise ships in pristine regions might be difficult. It would be useful to focus on regions with strong gradients in aerosol concentrations. The science questions are suitable for ships of opportunity because long-term measurements are needed to develop statistics and enable compositing of data over a wide variety of meteorological and aerosol regimes.

Science Question 2 – How does the susceptibility of clouds to changes in aerosol vary with both synoptic meteorological conditions and aerosol background state?

It is important to understand whether regions with high albedo and precipitation susceptibility are associated with low background aerosol concentrations and whether we can understand susceptibility in the context of the meteorological cloud-controlling factors and background aerosol. Measurements would enable scientists to examine the assumptions that have been used to make susceptibility maps from reanalysis. In addition to the measurements in the previous question, surface meteorological measurements and reanalysis would be needed to constrain cloud-controlling factors that cannot be determined from measured surface meteorology.

Science Question 3 – How can observations be used to assess the adjustments of cloud liquid water and cloud coverage to aerosol on diurnal to synoptic/seasonal timescales?

Observing ship tracks of different "ages" being traversed by the ships of opportunity would allow testing the hypothesis that liquid water path adjustments get stronger over time (Wang and Feingold 2009, Glassmeier et al. 2021). Long-term ship observations could also be used to test whether full observation of the diurnal cycle provides useful information to constrain models (e.g., Sandu et al. 2008 showed a strong effect of aerosol on the diurnal amplitude of marine stratocumulus liquid water path). These observations would be most useful on routes where the measuring ship frequently intersects aerosol tracks from other ships. Approaches would need to be developed to connect the ship emissions from other ships with features detected by the measurement ship or by satellites. Ship locations would need to be known and trajectory analysis conducted to connect the measurement locations with the ship emissions.

Session 3b -Aerosol-Cloud Interaction Processes

This second session on aerosol-cloud interactions focused on processes that are both important for aerosol indirect effects on Earth's radiative balance and poorly represented in climate models. This session discussed three science topics specific to regions with warm clouds in the coupled boundary layer: 1) cloud processing of aerosols, 2) activation of aerosol particles, and 3) cloud supersaturation, and then briefly discussed 4) how cold-cloud conditions would affect these relationships. Questions within these topics are well suited to opportunistic observations over remote oceans due to the current lack of observational data and the likelihood of sampling aerosols that have undergone repeated cycling within clouds. Ideal measurement locations would be warm stratocumulus cloud regions (e.g., Eastern Pacific and Eastern Atlantic) and clean marine regions (e.g., Southern Ocean). Workshop discussion focused primarily on warm clouds, in part because it was felt that commercial ship observations in non-polar regions were more feasible. However, satellite observations indicate that cold rain (produced by the ice phase) is prevalent over mid-latitude oceans, indicating that ice and/or mixed-phase clouds are also common in these regions (Mülmenstädt et al. 2015).

A common feature of these science topics is their reliance on mobility-based size distribution measurements using a well-characterized inlet. While this dependence introduces challenges for autonomous operation on commercial ships, these measurements cannot be retrieved from satellites. The minimum size range of the DMA required to address the questions below is 20-600 nm; a more useful range would be 10-800 nm. A submicron composition/hygroscopicity measurement would reduce uncertainty of these questions but may not be required for relatively clean marine conditions given their climatological consistencies. For aerosol-cloud-interaction processes in cold clouds, INP measurements would also be required. More information about measurement needs is in Table 1.

Science Question 1 – How do clouds change aerosol size distributions?

Since Hoppel's groundbreaking work in 1990 (Hoppel and Frick 1990), there has been little observational evidence quantifying the cloud-processing of aerosols. Models show a strong sensitivity of the accumulation-mode composition to in-cloud aqueous reactions, but the extent of the contribution of cloud processing to aerosol size and mass is unknown. Cloud processing of aerosols is most evident in particles that have few sources and repeated in-cloud cycling as is frequently the case for marine aerosol particles. A recent modeling study has shown that cloud processing of aerosol via collision-coalescence produces a characteristic change in the aerosol size distribution; the frequency of this process in marine clouds could be tested with long-term measurements of aerosol size distributions in the marine boundary layer (Hoffman and Feingold 2023). Ideal measurement locations would be away from continental influence. In addition to aerosol size distribution measurements, this question would require air mass history from trajectories/satellites, measurements of cloud-base height, and, if possible, measurement of aerosol composition.

Science Question 2 – Which aerosol particles activate to form cloud drops and is "closure" met?

Aerosol composition and activation is poorly characterized over much of the world's oceans, and it is unclear whether even having knowledge of aerosol size and a hygroscopicity parameter would be sufficient to predict activation of particles to form cloud drops. Comparing CCN concentrations derived from composition and size measurements to directly measured CCN concentrations would enable assessment of the importance of components that are not measured or are poorly characterized, such as organic components. Measurements of aerosol size distributions, aerosol hygroscopicity and/or composition, cloud condensation nuclei concentration, and measured or retrieved cloud drop number concentration would be necessary to answer this question.

Science Question 3 – What supersaturation is consistent with the observed cloud processing and when is supersaturation controlled by aerosol concentrations?

Climate models largely rely on parameterizations of cloud supersaturation (such as Abdul-Razzak et al. 1998), but few direct measurements over marine regions exist to constrain or validate these values. Opportunistic measurements of aerosol size distributions, aerosol hygroscopicity and/or composition, cloud condensation nuclei concentrations, and measured or retrieved cloud drop number concentration would enable the determination of which factors control in-cloud supersaturation and under what conditions. For example, in what regions and to what extent is supersaturation controlled by updraft velocity and cloud condensation nuclei concentrations as opposed to the aerosol number concentration?

Science Question 4 – How do cold conditions (i.e., glaciation) affect these relationships?

While the previous science questions focused on warm-cloud conditions, this one considers how cold conditions affect these processes. Ice nucleating processes are poorly understood and are important for cold clouds, which cover many parts of the globe and are poorly represented in climate models. There are many unanswered questions about the roles of CCN in cold clouds and the extent to which INP and secondary ice processes affect cold-cloud properties. This science question would require sampling in regions with cold clouds, such as arctic shipping lanes, and would require measurement of INP. Satellite observations and retrievals could assist in identification of cold clouds and provide information about cloud properties.

Session 4 – Science from a Limited Set of Feasible Instruments

While the first two days of the workshop were carefully scheduled to accommodate discussion of a predefined set of topics, the agenda for the third day was developed on the fly. The third day opened with a quick introduction to the XLeap real-time collaboration/brainstorming software. Participants were then asked to respond to the following question in XLeap: "What topics/questions/issues do you think need further discussion in a breakout session this afternoon? These can be topics raised in earlier sessions or new topics." Using this prompt, participants submitted their own ideas and commented on those submitted by other participants. Following discussion, related questions and ideas were merged and participants were then asked to vote on their highest-priority topics.

Participants identified the question, "What science questions could be addressed with the 5-6 most-feasible-to-deploy instruments identified in Monday's sessions?" as the highest priority for further discussion. This led to discussion about how to organize the breakout sessions, with participants deciding that two concurrent breakout sessions, each including both aerosol and cloud scientists, in contrast to several of the sessions the day before, would be most appropriate.

Before going into concurrent breakout sessions, participants revisited the feasibility of the measurements that had been discussed on the first day. Based on discussion from the previous two days, participants updated their votes on the scientific feasibility of various measurements. The following measurements received the most votes and were the basis for discussion in the breakout sessions:

- Surface meteorology
- Aerosol size distribution from optical particle counter
- CO mixing ratios
- Aerosol number concentration
- Aerosol optical properties (extinction, scattering, and/or absorption)
- Broadband shortwave and longwave radiation
- Ship position/navigation
- Cloud-base height from ceilometer
- Cloud-base temperature
- Bulk surface fluxes
- Sky conditions/cloud fraction from sky imager
- Liquid water path/integrated water vapor from microwave radiometer (This was not originally on the list but was added independently by both groups as a feasible measurement during the discussion.)

Participants were asked to address two questions regarding this set of measurements:

1) **In what way would this set of measurements on a commercial ship provide a unique and scientifically valuable set of measurements?**

2) **What science questions could be addressed with this set of measurements/instruments?**

Attendees noted a relative lack of in situ aerosol/cloud/radiation measurements over open oceans and that this set of measurements from commercial ships would provide useful information on the background state of aerosol and atmosphere for modeling and other analyses. They also noted that the "background" state of most of the oceanic atmosphere is not pristine due to ship and continental emissions, but that research cruises often concentrate on more remote ocean regions, which may not be representative. Therefore, data from commercial ships, when combined with existing data sets from targeted research cruises, could provide useful information about environmental variability within, near, and outside shipping lanes. Combined with back-trajectory calculations, this set of measurements could provide useful information on aerosol sources.

Another significant value is that long-term measurements on commercial ships would enable types of statistical analysis and compositing of data (e.g., by meteorological conditions) that cannot be done from short-duration research cruises. These types of analyses and data composites would be valuable for understanding environmental controls on different processes and for validation of model simulations and satellite-retrieval assumptions. When combined with satellite retrievals, these measurements could fill critical gaps such as cloud-base height and aerosol properties under clouds that are unobtainable from geostationary satellites alone. Attendees also noted that these data could be useful to identify variability, phenomena, or processes in certain ocean regions that are not well captured in current models, which could lead to development of more targeted short-term research campaigns with advanced instrumentation to address these questions.

Participants quickly brainstormed multiple science questions that could be addressed with this limited set of feasible measurements, many of which were discussed in more detail in the science breakout sessions. They felt that this limited set, especially if combined with satellite data, could be used to investigate cloud adiabaticity, environmental controls on variability in cloud properties, cloud radiative cooling, and liquid-water path adjustments due to aerosol-cloud interactions. They also thought these measurements would be useful to address several questions about surface fluxes and their relationships with aerosols and clouds, including how the relationships differ for coupled and decoupled boundary layers or within and at the boundaries of different cloud mesoscale organizations.

The aerosol measurements would allow investigation of the variability of aerosol in the marine boundary layer and how aerosol number concentrations differ between the remote ocean, traditional shipping lanes, and the coastal sites that are often used as proxies for marine aerosol properties. The measurements would help to constrain estimates of the direct radiative impacts of aerosol in different ocean regions and may identify regions with significant fractions of absorbing aerosol that are not identified in models (and would hence warrant further investigation). Combining these measurements with satellite data would enable investigation of how extreme dust or smoke events contribute to marine boundary-layer aerosol variability. Measurements from an optical particle counter combined with modeled aerosol volume concentrations may provide enough information to decrease the uncertainty in aerosol composition models over remote regions. Measurements from two condensation particle counters with different size thresholds could be used to identify NPF events. Understanding the frequency and location of NPF in the marine boundary layer could inform targeted research campaigns with more advanced instruments to understand the importance of NPF on marine clouds (i.e., through mechanistic studies that identify precursors and nucleation rates).

A statistically significant data set spanning a range of meteorological conditions, especially when combined with models, reanalysis, and/or satellite retrievals, would also enable the investigation of many questions about aerosol-cloud interactions, including general questions about the correlations between aerosols and clouds. If the data set included sampling of ship tracks, scientists could start to answer under which conditions ship tracks will form.

Attendees also identified a second set of measurements/instruments that they felt were moderately feasible (with ~1 year of development): turbulence/updraft from Doppler lidar, mobility-based aerosol size distribution, CCN, INP filters, and aerosol composition. Participants were asked, “What additional science questions could be addressed by adding one of these instruments?” The two most valuable measurements were felt to be the mobility-based aerosol size distribution and the turbulence/updraft from Doppler lidar, and most of the discussion centered on those two measurements, although the others were discussed briefly.

Adding mobility-based size distribution measurements would make it possible to address a host of science questions related to boundary-layer aerosol processes and aerosol-cloud interactions (see Sessions 1a and 3b). These measurements would especially improve initialization of parcel models, improve CCN predictions, and help more mechanistic evaluation of the aerosol indirect effect through evaluation of cloud supersaturation ensembles. These measurements could also provide direct, quantitative evidence of cloud processing of aerosol in both “clean” and polluted conditions. Other cloud effects of aerosols (and vice versa) could be retrieved from measurements of the Hoppel minimum. Mobility-based size distributions would permit assessment of when and where we see evidence of newly formed particles and of their contribution to CCN and help address under what conditions these particles can grow to become CCN and their survival probability.

Combining measurements of cloud-base updraft speed from Doppler lidar with aerosol size distributions would allow parcel model calculations of cloud-base drop number concentration (in well-mixed conditions). Doppler lidar measurements would also provide more information for addressing questions related to boundary-layer coupling indices. The Doppler lidar measurements would provide information on whether the boundary layer is coupled with the surface. Also, the backscatter from Doppler lidar can be combined with that from the ceilometer to derive profiles of drizzle properties below cloud base (e.g., Ghate et al. 2021), thus providing more information on precipitation susceptibility to aerosol changes.

Adding aerosol composition measurements would provide context to the aerosol concentration and size distribution measurement and would allow some source attribution, such as whether the aerosol derived from advected biomass burning, urban, or continental sources. Adding aerosol composition would reduce the uncertainty of quantifying aerosol-cloud interactions, although in many regions this may be a second-order effect because of the observed climatological consistency of the accumulation mode composition.

Adding INP filters would allow testing of existing INP parameterizations in many additional marine locations/regimes. INP filters collected in polar regions would also allow better constraints on aerosol-mixed-phase cloud interactions that are prevalent in polar marine stratus cloud decks.

Participants disagreed on whether a direct measurement of CCN concentration at multiple supersaturations from commercial instruments was moderately feasible but noted that an estimate of CCN concentration could be obtained from mobility-based aerosol size distribution measurements. Surface CCN concentration measurements would be useful to constrain the CCN budget at cloud base. Recent studies report some success in using vertical profiles of aerosol optical properties to predict CCN aloft. Coupling this measurement with the vertical structure of wind/turbulence from Doppler lidar would help to understand the cloud drop size distribution at the base of low-level clouds.

Key Elements of a Pilot Program

The second highly ranked topic identified in the discussion on the morning of Day 3 was, “Could we do an exercise to scope out a pilot project?” Participants agreed they wanted to discuss this topic in one group, rather than breaking into smaller groups. As the discussion progressed, participants focused more on key elements that would be necessary for any pilot program, rather than outlining a specific example project.

The following key elements of a successful pilot program were identified by participants:

- Science plan
- Science team with the necessary breadth of expertise
- Definition of metrics for success
- Risk management plan
- Well-justified instrumentation list based on science questions
- Plan for instrument development, hardening, packaging into modules, and operational configuration
- Phased testing of instrument packages and autonomous operations (e.g., beginning with controlled laboratory and local outdoor tests, progressing to testing on a local marine platform such as a buoy, barge, or ferry, and moving on to testing on a vessel with onboard technicians)
- Plan for instrument maintenance and calibration
- Plan for quality control, data processing, data flow, data archiving, and data distribution
- Plan for vessel recruitment
- Collaboration with or leveraging of other existing activities for vessel recruitment, development of instruments, testing instrument packages, deploying with established instruments, and/or processes for data QA/QC, processing, and distribution
- Communication and feedback plan for engaging the broader community
- Complete and detailed timeline of activities.

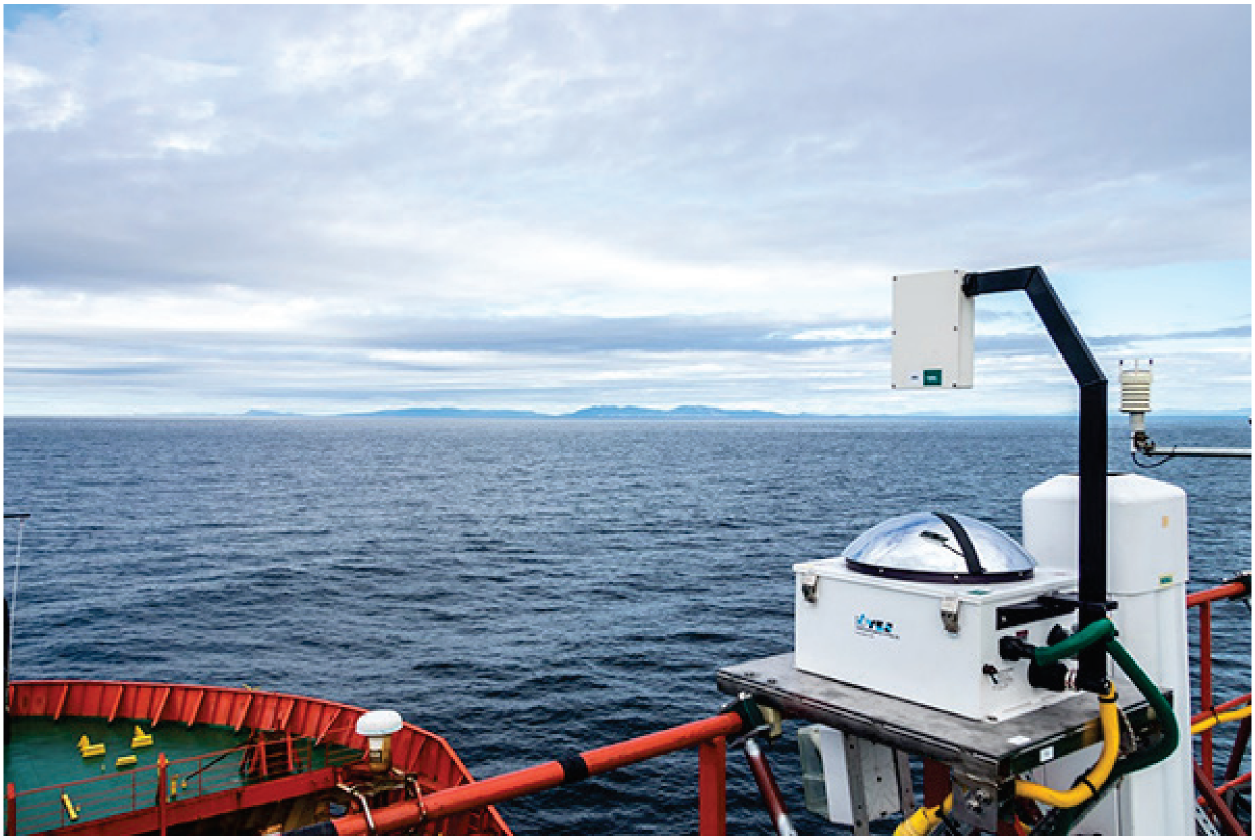
Coordination with Other Activities

During the preparation and implementation of the workshop, attendees identified previous, existing, or planned ship-based observational activities that would be useful to learn from and/or coordinate with. Along with the intensive shipborne field campaigns regularly conducted by NOAA and other agencies, the following activities were noted:

- ARM has conducted previous mobile facility deployments on a commercial ship (MAGIC) and on an Australian Antarctic Division resupply ship (Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean [MARCUS]). However, it was noted that although both campaigns were conducted on non-research vessels, full-time technicians were deployed with the suite of instruments, which would not be sustainable for a long-term observational program. Participants also noted that leveraging or learning from ARM’s processes in data ingestion, curation, distribution, and archiving could be valuable.
- The DOE Wind Energy Technologies Office (WETO) has several measurement activities focused on offshore wind resources including lidar buoys (https://www.pnnl.gov/projects/lidar-buoy-program) and the 3rd Wind Forecasting Improvement Project (WFIP3; https://www2.whoi.edu/site/wfip3/), which includes deployment of unattended instruments on a barge during targeted observing periods for characterization of the marine boundary-layer structure. This program also has a mature data QA/QC and archiving process.
- The Science Research on Commercial Ships (Science RoCS) initiative (https://sciencerocs.org/) is developing a framework for collaborating with the marine industry to establish a network for ocean observation to greatly expand the ability to observe the atmosphere and upper ocean waters. The initiative envisions a future where commercial vessels are equipped with a suite of "plug & play" scientific sensors. These would include the measurement of water properties and currents, as well as oceanic chemical and

biological parameters—optimized for a vessel's trade route to address societally relevant questions, with the data disseminated broadly for the advancement of scientific knowledge.

- The NOAA Ships of Opportunity Program (SOOP; https://www.aoml.noaa.gov/phod/soop/index.php) supports the implementation of a network of cargo vessels, cruise ships, and research vessels to deploy scientific instruments that collect oceanographic observations such as ocean temperature profiles, salinity, and temperatures along a ship's path, and surface water CO_2. The SOOP project also developed and currently maintains the Shipboard Environmental Data Acquisition System (SEAS), which is software that collects and transmits oceanic and meteorological observations.
- A pilot project to deploy instruments to measure greenhouse gases and aerosol radiative effects on Maersk vessels has been undertaken by NOAA's Global Monitoring Laboratory, Accenture, and SilverLining, although only limited public information is available as of this workshop (https://www.silverlining.ngo/platforms-of-opportunity).



A sky imager and ceilometer collected data during the MARCUS field campaign. Photo courtesy of Janek Uin, Brookhaven National Laboratory.

References

Abdul-Razzak, H, SJ Ghan, and C Rivera-Carpio. 1998. “A parameterization of aerosol activation: 1. Single aerosol type.” *Journal of Geophysical Research – Atmospheres* 103(D6): 6123–6131, https://doi.org/10.1029/97JD03735

Carslaw, KS, LA Lee, CL Reddington, KJ Pringle, A Rap, PM Forster, GW Mann, DV Spracklen, MT Woodhouse, LA Regayre, and JR Pierce. 2013. “Large contribution of natural aerosols to uncertainty in indirect forcing.” *Nature* 503: 67–71, https://doi.org/10.1038/nature12674

Christensen, MW, A Gettelman, J Cermak, G Dagan, M Diamond, A Douglas, G Feingold, F Glassmeier, T Goren, DP Grosvenor, E Gryspeerdt, R Kahn, Z Li, P-L Ma, F Malavelle, IL McCoy, DT McCoy, G McFarquhar, J Mülmenstädt, S Pal, A Possner, A Povey, J Quaas, D Rosenfeld, A Schmidt, R Schrödner, A Sorooshian, P Stier, V Toll, D Watson-Parris, R Wood, M Yang, and T Yuan. 2023. “Opportunistic experiments to constrain aerosol effective radiative forcing.” *Atmospheric Chemistry and Physics* 221): 641–674, https://doi.org/10.5194/acp-22-641-2022

Diamond, MS, HM Director, R Eastman, A Possner, and R Wood. 2020. “Substantial Cloud Brightening from Shipping in Subtropical Low Clouds.” *AGU Advances* 11): e2019AV000111, https://doi.org/10.1029/2019AV000111

Fairall, CW, EF Bradley, JE Hare, AA Grachev, and JB Edson. 2003. “Bulk Parameterization of Air–Sea Fluxes: Updates and Verification for the COARE Algorithm.” *Journal of Climate* 164): 571–591, https://doi.org/10.1175/1520-0442(2003)016<0571:BPOASF>2.0.CO;2

Flores, JM, G Bourdin, AB Kostinski, O Altaratz, G Dagan, F Lombard, N Haëntjens, E Boss, MB Sullivan, G Gorsky, N Lang-Yona, M Trainic, S Romac, CR Voolstra, Y Rudich, A Vardi, and I Koren. 2021. “Diel cycle of sea spray aerosol concentration.” *Nature Communications* 12: 5476, https://doi.org/10.1038/s41467-021-25579-3

Garay, MJ, R Davies, C Averill, and JA Westphal. 2004. “Actinoform Clouds: Overlooked Examples of Cloud Self-Organization at the Mesoscale.” *Bulletin of the American Meteorological Society* 85(10): 1585–1594, https://doi.org/10.1175/BAMS-85-10-1585.

Glassmeier, F, F Hoffmann, JS Johnson, T Yamaguchi, KS Carslaw, and G Feingold. 2021. “Aerosol-cloud-climate cooling overestimated by ship-track data.” *Science* 371(6528): 485–489, https://doi.org/10.1126/science.abd3980

Hoffmann, F, and G Feingold 2023. “A note on aerosol processing by droplet collision-coalescence.” *Geophysical Research Letters* 50: e2023GL103716, https://doi.org/10.1029/2023GL103716

Hoppel, W and G Frick 1990. “Submicron aerosol size distributions measured over the tropical and south Pacific.” *Atmospheric Environment. Part A. General Topics* 243): 645–659, https://doi.org/10.1016/0960-1686(90)90020-N

Jones, CR, CS Bretherton, and D Leon. 2011. “Coupled vs. decoupled boundary layers in VOCALS-Rex.” *Atmospheric Chemistry and Physics* 11: 7143–7153, https://doi.org/10.5194/acp-11-7143-2011

Lewis, Ernie R. 2016. Marine ARM GPCI Investigation of Clouds (MAGIC) Field Campaign Report. U.S. Department of Energy. DOE/SC-ARM-16-057, https://doi.org/10.2172/1343577

Mülmenstädt, J, O Sourdeval, J Delanoë, and J Quaas. 2015. "Frequency of occurrence of rain from liquid-, mixed-, and ice-phase clouds derived from A-Train satellite retrievals." *Geophysical Research Letters* 42(15), 6502–6509, https://doi.org/10.1002/2015GL064604

Sandu, I, J Brenguier, O Geoffroy, O Thouron, and V Masson. 2008. "Aerosol Impacts on the Diurnal Cycle of Marine Stratocumulus." *Journal of the Atmospheric Sciences* 65(8): 2705–2718, https://doi.org/10.1175/2008JAS2451.1

Sandu, I, and B Stevens. 2011. "On the Factors Modulating the Stratocumulus to Cumulus Transitions." *Journal of the Atmospheric Sciences* 68(9): 1865–1881, https://doi.org/10.1175/2011JAS3614.1

Smith, SR, N Lopez, and MA Bourassa. 2016. "SAMOS air-sea fluxes: 2005–2014." *Geoscience Data Journal* 31): 9-19, https://doi.org/10.1002/gdj3.34

U.S. DOE. 2019. Atmospheric Radiation Measurement (ARM) User Facility ARM Mobile Facility Workshop Report. DOE/SC-0197.

Wang, H, and G Feingold. 2009. "Modeling Mesoscale Cellular Structures and Drizzle in Marine Stratocumulus. Part I: Impact of Drizzle on the Formation and Evolution of Open Cells." *Journal of the Atmospheric Sciences* 66(11): 3237–3256, https://doi.org/10.1175/2009JAS3022.1

Appendices

Appendix A – Agenda

BER Ship Observations Workshop

March 18-20, 2024
Remote workshop conducted over Zoom
All times Eastern

March 18, 2024

11:00 AM – 12:15 PM Introduction and Goals of the Workshop

11:00 – 11:05 Welcome

11:05 – 11:20 Attendee Introductions

11:20 – 11:40 Workshop Charge

11:40 – 12:00 Workshop agenda and plan

12:00 – 12:15 Discussion

12:15 PM – 12:30 PM Break

12:30 PM – 2:15 PM Session 1 – Ships of Opportunity – Background and Logistical Issues

- Session goal: Give workshop attendees background on working on commercial ships
- Expected outcomes: Document primary logistical challenges to be addressed for any pilot project and note potential solutions

12:30 – 12:45 Plenary Session

Presentation – Kerry Strom, WHOI

12:45 – 2:15 Breakout Sessions – break out into 2 assigned groups for discussion

Breakout 1 (Nicki Hickmon, facilitator)

Breakout 2 (Ernie Lewis, facilitator)

2:15 PM – 2:45 PM Break

2:45 PM – 4:30 PM Session 2 – Instrumentation and data

- Session goal: Understand the feasibility and challenges of deploying given instrument types on commercial ships
- Expected outcomes: Ranking of instrumentation in terms of feasibility/readiness for commercial ship deployment

2:45 – 3:15 Plenary Session

- Presentation – Trish Quinn, NOAA
- Presentation – Raghu Krishnamurthy, PNNL

3:15 – 4:30 Breakout Sessions

Breakout 1 – Aerosols/greenhouse gases/ocean (Markus Petters, facilitator)

Breakout 2 – Clouds/radiation/atmosphere (Adam Theisen, facilitator)

4:30 PM – 4:45 PM Break

4:45 PM – 5:30 PM Summary/Questions/Discussion (plenary)

March 19, 2024

11:00 AM – 11:15 AM Plans for Day 2 (plenary)

- Session goals: discuss a set of high-priority BER-relevant science questions that might be well suited to an initial pilot project

11:15 AM – 12:55 PM Science Session 1

Breakout 1a – Boundary-layer structure including dynamics, thermodynamics, and cloud structure (Virendra Ghate, facilitator)

Breakout 1b – Aerosol characterization, sources, and transit (Allison Aiken, facilitator)

12:55 PM – 1:25 PM Break

1:25 PM – 3:05 PM Science Session 2

Breakout 2a – Regional cloud, radiation, and boundary-layer properties from combined ship and satellite measurements (Matt Christensen, facilitator)

Breakout 2b – Air-sea exchange and boundary-layer aerosol formation (Tim Bertram, facilitator)

3:05 PM – 3:20 PM Break

3:20 PM – 5:00 PM Science Session 3

Breakout 3a – Aerosol-cloud albedo and precipitation susceptibility (Rob Wood, facilitator)

Breakout 3b – Aerosol-cloud interaction processes (Lynn Russell, facilitator)

5:00 PM – 5:30 PM Summary/Questions/Issues (Plenary)

March 20, 2024

11:00 AM – 12:30 PM Summary of Days 1-2; Plans for Day 3 (plenary)

XLeap Session: What topics/questions/issues do you think need further discussion in a breakout session this afternoon? These can be topics raised in earlier sessions or new topics.

12:30 PM – 1:00 PM Break

1:00 PM – 1:45 PM Session 1

(Breakouts TBD)

1:45 PM – 2:30 PM Session 2

(Breakouts TBD)

2:30 PM – 3:00 PM Break

3:00 PM – 5:30 PM Workshop report planning (start in plenary; then breakouts)

(Breakouts TBD)

Appendix B – Acronyms

3D	three-dimensional
ACTIVATE	Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment
ACSM	aerosol chemical speciation monitor
AERI	atmospheric emitted radiance interferometer
AMF2	second ARM Mobile Facility
AMS	aerosol mass spectrometer
APS	aerodynamic particle sizer
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
ASSIST-II	Atmospheric Sounder Spectrometer by Infrared Spectral Technology
BER	Biological and Environmental Research
BORCAL	Broadband Outdoor Radiometer Calibration
CCN	cloud condensation nuclei
CFD	computational fluid dynamics
CO	carbon monoxide
CO_2	carbon dioxide
COARE	Coupled Ocean-Atmosphere Response Experiment
CPC	condensation particle counter
DMA	differential mobility analyzer
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EEZ	Exclusive Economic Zone
ENA	Eastern North Atlantic
GCSS	GEWEX Cloud Systems Study
GEWEX	Global Energy and Water Cycle Experiment
GPCI	GCSS Pacific Cross-section Intercomparison
HTDMA	humidified tandem differential mobility analyzer
IMU	inertial measurement unit
IN	ice nuclei
INP	ice nucleating particles
KAZR	Ka-band ARM Zenith Radar
LANL	Los Alamos National Laboratory

LWP	liquid water path
MAGIC	Marine ARM GPCI Investigation of Clouds
MARCUS	Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean
MOSAiC	Multidisciplinary drifting Observatory for the Study of Arctic Climate
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NOx	nitrogen oxides
NPF	new particle formation
PBL	planetary boundary layer
PMEL	Pacific Marine Environmental Laboratory (NOAA)
PNNL	Pacific Northwest National Laboratory
QA/QC	quality assurance/quality control
Science RoCS	Research on Commercial Ships
RWP	radar wind profiler
SBIR	Small Business Innovation Research
SEAS	Shipboard Environmental Data Acquisition System
SHIPRAD	ship radiation system
SOOP	Ships of Opportunity Program
SST	sea surface temperature
TBS	tethered balloon system
TKE	turbulent kinetic energy
TWST	Three-Waveband Spectrally agile Technique
UAS	uncrewed aerial system
UHSAS	ultra-high-sensitivity aerosol spectrometer
UPS	uninterruptible power supply
UV	ultraviolet
WETO	Wind Energy Technology Office (DOE)
WFIP3	3rd Wind Forecasting Improvement Project
WHOI	Woods Hole Oceanographic Institution
WMO	World Meteorological Organization

Appendix C – Aerosol Measurements Table

Table 2. *Summary of aerosol measurements discussed in the Instruments/Data breakout session.*

Measurement	**Scientific Priority [1 low, 3 high]**	**Feasibility [1 low, 3 high]**	**Summary**
Aerosol size distribution 10-800 nm based on electric mobility	2.8	2.1	Deploying instruments to measure mobility-based size distribution is moderately feasible, but will require hardening to prevent arcing, cleaning procedures of the interior of the column, improved flow control, and software development to ensure unattended operation. It will also require development of crew procedures to refill liquid reservoirs. Size distribution measurements will also require an inlet that conditions the air samples. As these instruments require sealed radioactive sources or soft X-ray sources, deployment will require development of safety protocols for the crew and regulatory compliance for operating the instruments worldwide.
Aerosol size distribution 60-30,000 nm based on optical properties or inertia	2.5	2.6	Optical measurements were considered feasible with minor maintenance needs such as adjustment of lasers in port, periodic replacement of internal filters, and regular calibrations. Some development on communications may be needed. Larger particle sizes will be more challenging and measurements of coarse-mode particles will require special attention to sample lines to mitigate particle losses. Instruments should be placed as high as possible to minimize sea spray artifacts. Use of uncrewed aerial system (UAS)/TBS inlets may be possible.
CCN concentration as a function of water supersaturation	2.4	1.6	May require substantial development. Current instruments require regular maintenance such as water refill/drain every few days; inlets are prone to clogging in marine environments; internal flooding is likely to occur; and troubleshooting and maintenance require trained technicians. Chemicals for supersaturation calibration need to be properly stored; CCN calibration requires mobility size distribution measurement and needs a trained technician.
Aerosol number concentration	2.7	2.5	CPCs require either butanol or water as a working fluid, which would need to be fitted with a larger reservoir and replenished at a low level to avoid internal flooding. Butanol may become contaminated with water condensed from the air over time. Instruments can clog with heavy loading from sea spray or exhaust – flows need to be checked routinely. Using butanol may require additional safety constraints. Instruments are sensitive to temperature changes and need a temperature-controlled enclosure.

Measurement	Scientific Priority [1 low, 3 high]	Feasibility [1 low, 3 high]	Summary
Aerosol vertical profile	not ranked	not ranked	Vertical distribution of aerosol backscatter or extinction measured by lidar. Polarized lidar technologies could provide this information but would need a surface reference. Viewports would need to be cleaned regularly; development of automatic systems for cleaning would be useful. Need to know pointing direction or have a stabilized platform to correct for ship pitch and roll. Eye safety concerns. Careful calibration of optics required. Advanced systems capable of calibrated backscatter or extinction are expensive.
Online aerosol composition	1.9	1.2	Aerosol mass spectrometers (AMSs) are not realistic for unattended operations. The ACSM has been proven to operate on a ship, but it is a large, complex instrument; there would be great benefit in reducing the size of the system. Time resolution of measurements depends on instrument, component, and size. Size-resolved composition likely requires 6-12 hours of averaging for a particle-time-of-flight-capable AMS. Sea salt will not be measured independently. Measuring the volatility of aerosol provides limited insight into composition without a spectrometer.
Offline aerosol composition (i.e., filters)	2.0	2.0	Successful filter sampling will require conditional sampling by wind-sector, possible real-time screening of periods with ship exhaust, improved samplers to rotate filters, and protocols to store, retrieve, and process the filters. Additional cost/effort will be required to process filters to usable data products.
Ice nucleating particle measurements	2.1	1.5	Along with the above general concerns for filter samples, INP samples require frozen storage. This may be possible for shorter voyages but may be challenging for longer voyages; also logistics challenges in shipping back for analysis.
Aerosol optical depth	2.1	2.5	Handheld sun photometers have been deployed but require trained personnel to take measurements. Shadowband radiometer or CIMEL sun photometer have moving parts that increase the possibility for failure on a ship. Optics would need to be cleaned regularly. Data processing would need to handle removal of cloud contamination; thin cirrus can be problematic.
Aerosol hygroscopicity	1.8	1.3	Measurement would require capability for remote monitoring and a trained technician. The technique is currently not feasible for unattended measurements. Significant instrument development is needed for robust, field-deployable aerosol water-uptake measurements on a commercial vessel.
CO mixing ratio as a tracer for ship exhaust	2.4	3.0	Commercial instruments exist and deployment is feasible; may be best to include as part of a package with other greenhouse gas measurements. Some concerns were noted about detectability limits.

Measurement	Scientific Priority [1 low, 3 high]	Feasibility [1 low, 3 high]	Summary
Ozone concentration	1.3	1.6	Ozonesondes require a significant level of effort, multiple calibrations prior to launch, and a self-leveling platform. Likely unfeasible on a commercial vessel without a dedicated technician. Ozone gas analyzers may be feasible but the sensitivity for scientific use in understanding aerosol aging is unclear.
Aerosol flux	1.5	1.0	This is a very difficult technique, even on land; unfeasible to do autonomously on a commercial ship.
Black carbon mass or number concentration	1.9	2.2	Commercial instruments exist that can operate for long periods with little maintenance. Challenges include large data volumes, instrument sensitivity to relative humidity, and the need for regular calibrations. Current size-resolving instruments such as the single particle soot photometer are limited to particles with diameters > 70 nm and may miss some smaller black carbon particles from ship exhaust or other combustion sources.
Aerosol scattering	2.1	2.4	Nephelometers require an air stream, flow control, and environmental temperature control. Aerosol would need to be dried, preferably not by heating; this could be challenging in a marine environment. Minimal maintenance is required.
Aerosol extinction	2.1	2.5	Cavity phase-shift or cavity ringdown techniques are feasible. Optics cleaning may be necessary. Some instruments may not need inlet or calibration but exposure to elements is an issue.
Aerosol absorption	2.1	2.4	Several techniques exist, including some new low-cost instruments developed over the last few years. Instruments may require periodic window cleaning and impactor cleaning. Frequent calibration of many of these methods is essentially not possible. Post-processing and auxiliary measurements (such as scattering coefficient) might be required. Accuracy is typically low.
Near-surface pCO_2	1.8	2.3	These measurements have been done by the ocean community for decades on research ships and commercial vessels.
Sea surface temperature (skin temperature)	2.6	2.7	Multiple instruments exist for measuring in situ sea surface temperature. Measurement of skin temperature, which is more desirable for the atmospheric science questions, will require downward-looking infrared radiometers. These have been deployed on research vessels, but development may be needed for unattended operations. Primary challenges are siting the instrument so it has a proper view angle of the ocean and additional measurements to detect factors that will impact observations such as ship's wake and sun glint.
Atmospheric CO_2	2.0	2.8	Commercial gas concentration analyzers are feasible for autonomous operation on a ship. They do not require stack and pumps, just a protected inlet. Minimal maintenance is required, only calibration every 6 months.

Measurement	Scientific Priority [1 low, 3 high]	Feasibility [1 low, 3 high]	Summary
SO_2 concentration	2.2	2.1	Multiple techniques exist at a range of costs and sensitivities. Would likely need further development to increase sensitivity to address science questions of sulfur chemistry in the marine atmosphere. Filters need to be changed weekly; calibration is generally stable but calibration and sampling lines should be checked regularly in port.

Appendix D – Cloud, Radiation, Atmospheric State Measurements Table

***Table 3**. Summary of cloud, radiation, and atmospheric state measurements discussed in the Instruments/Data breakout session.*

Measurement	Scientific Priority (1 [Low] – 3 [High])	Feasibility (1 [Low] – 3 [High])	Summary
Surface meteorology	3.0	3.0	Surface meteorology has a high scientific priority and is the most feasible measurement to deploy on a ship. While there are many all-in-one systems that could be deployed, it would be extremely beneficial to record 3D winds and relative humidity at 10-20 Hz in addition to routine temperature and pressure measurements. These high temporal wind and humidity measurements are used in the calculation of bulk fluxes. These observations should be made on the front mast of a ship ahead of any ship structure for undisturbed flow. There is value in deploying redundant systems on the ship to minimize data quality issues from the ship structure. The maintenance needs are low, requiring yearly calibrations for some components. Depending on the ship track, icing could be problematic, necessitating the need for heated sensors.
Ship position/navigation information	2.9	3.0	Ship position is necessary to put shipborne measurements into context. It is not anticipated that ship navigation information will be readily supplied from the commercial vessels so it will be important for any system to include a navigation system for location information. These systems are already deployed on ships and are very robust. It is important to understand the lifetime of the systems that are being deployed.
Cloud-base heights	3.0	2.9	Cloud-base heights are a high priority for science as they are important for understanding the boundary-layer and cloud structure. Ceilometers are widely used for observing cloud-base height, which can also be derived from the (raw or calibrated) backscatter reported by any other lidars (e.g., Doppler lidar). In addition to the cloud-base height, ceilometers also report the particulate backscatter, which can be used to derive below-cloud aerosol and rain properties. However, these require calibration of the lidar backscatter and tracking its changes over time, which can be a significant challenge for autonomous operation. Many commercially available systems are feasible to deploy for long-term unattended operations. Depending on systems, blowers could keep the window clear, but in some cases, such as with Doppler lidars, a mechanism to automatically clean the window will need to be developed.

Measurement	Scientific Priority (1 [Low] – 3 [High])	Feasibility (1 [Low] – 3 [High])	Summary
Radiation	2.9	2.9	Radiation measurements are scientifically important and feasible to deploy for unattended operations. A wide range of radiation measurements are possible, including broadband, narrow field of view, photosynthetic, UV, hyperspectral, etc., but broadband radiation measurements would be the most important for a pilot project. Systems that have been deployed on ships, like ARM's SHIPRAD (portable radiation package), have proven robust. It may be necessary to deploy measurements on opposite sides of a ship to correct for shading from the ship. It is equally important to have a clear view of the sky and to be forward of the exhaust stack. Aspirated/heated radiometers should be considered (depending on region) to mitigate icing or water buildup on the lenses. Radiometers should be swapped out yearly for calibration, like ARM's Broadband Outdoor Radiometer Calibration (BORCAL) process. An IMU should be co-located with the sensors and ship motion should be considered or remediated, such as by tilt stabilization. The deployment of a sensor for photosynthetically active radiation could be beneficial for connecting to the oceanic measurement community for ocean color and biological measurements. These sensors are low-cost but could expand the user base of these systems.
Sky conditions (sky imager)	2.4	2.7	While ranked as only medium scientific priority, the deployment of cameras or sky imagers to understand sky conditions (cloud type, cloud cover, cloud motion) is feasible for unattended operations and was noted as necessary for three of the scientific questions. While there may not be much hardware development necessary, there would likely be software development necessary to retrieve the parameters of interest while on a moving ship. The data requirements of this processing could be challenging, depending on the communications bandwidth, as there would be many images to transfer. A solution could be in the form of edge computing that could process the images on site and transfer the retrieved data back.
Surface fluxes	2.4	2.7	Surface fluxes are a medium science priority that are feasible to deploy at sea, as shown by NOAA (Air-Sea flux system) and others. Alternatively, bulk fluxes could be derived from appropriate meteorological measurements using the Coupled Ocean-Atmosphere Response Experiment (COARE) algorithm. Additionally, it would be ideal to measure the sea surface temperature using an infrared radiometer. Any of these approaches would require corrections for ship motion, necessitating a co-located IMU.

Measurement	Scientific Priority (1 [Low] – 3 [High])	Feasibility (1 [Low] – 3 [High])	Summary
Turbulence/updraft velocity	2.4	2.6	Doppler lidars can retrieve boundary-layer turbulence, updraft velocity, and turbulent kinetic energy (TKE) dissipation rate estimates. These systems are fairly robust but would require some effort to deploy autonomously at sea, such as further marine hardening of the frame and an automated window cleaning system. A co-located IMU would be required to correct for ship motion, as has been done previously by ARM for these types of systems. A stabilizer could reduce errors in retrievals for instantaneous winds but is not necessarily needed when averaging the winds. As discussed with the cloud-base heights, a shield would be required as a failsafe to ensure the system does not scan outside the intended focus area. Turbulence statistics can be gathered from 3D sonic anemometers but these will be affected by the flow of the ship. Similarly to the surface fluxes, it would be beneficial to understand how the airflow is affected by the ship to correct for it. Ship perturbations of airflow could impact the lower gates of the Doppler lidar as well, depending on the vertical impact of the ship's disturbance footprint.
PBL height	2.6	2.5	PBL height was deemed to be a high scientific priority but was lower in feasibility than other lidar measurements. While the PBL can be retrieved from most of the backscatter lidar systems, it was noted that lidar-based PBL heights have greater uncertainty than those determined by a radiosonde under certain conditions. Autosonde launchers would be extremely costly and complicated to operate unattended at sea. A radar wind profiler (RWP) could perhaps be used to provide more accurate PBL heights, but some research would be needed to verify this. Both the lidars and RWP are feasible to operate on the ship, with the RWPs being more complicated to install and having a larger footprint.
Cloud-base temperature	2.0	2.5	Cloud-base temperatures can be measured with an infrared radiometer that is feasible to deploy on a ship, as ARM has done in past shipborne campaigns. Cloud-base temperature has a medium scientific priority, although it was discussed as providing additional value when coupled with a ceilometer for transitional zones as well as for cloud adiabaticity.
Liquid water path	2.7	2.4	Liquid water path (LWP) is of high scientific value but presents some challenges in measuring autonomously. Microwave radiometers are a base instrument for measuring LWP and precipitable water vapor, but it must be ensured that the covers are not punctured (which would cause substantial damage to the instrument) and that the blower fans are clean and running. The turnaround for repairs can also be very long depending on the vendor. Calibration of the system requires liquid N_2. This system could benefit from an automated cleaning system as well as camera monitoring. The data processing is trained using a neural network: this has been done by ARM for maritime data but is challenging.

Measurement	Scientific Priority (1 [Low] – 3 [High])	Feasibility (1 [Low] – 3 [High])	Summary
Surface precipitation	2.3	2.3	Precipitation is a medium scientific priority but some development is required to measure it effectively at sea. Precipitation rate and accumulation would be core measurements. Additional information such as precipitation size distribution could be provided by some instruments. ARM has previously deployed siphon, optical, and acoustic rain gauges as well as laser disdrometers that are deployed as a pair orthogonal to one another. Instruments deployed on a ship should be calibrated against a standard on land to understand the performance across a range of rain rates and conditions. It would be beneficial to deploy redundant measurements on a ship to ensure accurate rain rates and to quality-control the data due to interferences from sea spray and the ship structure. Because of the speed of the ship, precipitation will be falling at an appreciable angle, which might yield inaccurate measurements for some instruments.
Cloud optical depth	2.3	2.0	Cloud optical depth is a medium scientific priority but some development would be required to measure it autonomously at sea. Multi-filter shadowband radiometers could be deployed, but they have moving parts that are not ideal for unattended operations. A sun photometer could be operated in a zenith-pointing mode to retrieve optical depth. These systems require routine maintenance to ensure that the windows are clean and the tube is not obstructed. Zenith-pointing, narrow-field-of-view instruments with multiple visible spectral channels, such as the Aerodyne Three-Waveband Spectrally agile Technique (TWST) system, can retrieve cloud optical depth but would need more development for unattended operations.
Profiles of temperature/water vapor	2.1	1.8	Profiles of temperature and water vapor are medium scientific priority but are difficult to achieve for autonomous operations. Radiometers like a G-band water-vapor profiling system or a microwave temperature profiler could be used, but it is unknown how viable they are for unattended operations. Interferometers such as the atmospheric emitted radiance interferometer (AERI) or Atmospheric Sounder Spectrometer by Infrared Spectral Technology (ASSIST-II) could be used to measure boundary-layer profiles and have been deployed on ships, but doing so would add complexity, as previously noted. A commercial differential absorption lidar could be viable for unattended operations on a ship but the current commercial systems have a large footprint and retrieve only water vapor.
Cloud-top height/cloud thickness	1.8	1.7	Cloud-top height/cloud thickness could be measured using lidar for optically thin clouds, but satellite or radar data would be required for most other clouds. Radars would add to the complexity of any deployment. While the Ka-band ARM Zenith Radar (KAZR) is robust, it require routine checks and maintenance and has a large footprint. It would be beneficial to look towards Department of Defense (DOD) capabilities, as some DOD Small Business Innovation Research (SBIR) participants have produced small, portable, X-band, phased-array radars that could be viable on a ship if they were marine hardened.

Measurement	Scientific Priority (1 [Low] – 3 [High])	Feasibility (1 [Low] – 3 [High])	Summary
Cloud droplet number Concentration	2.1	1.6	While a medium scientific priority, cloud droplet number concentration was mentioned in three of the science questions. This quantity can be derived from cloud thickness (radar+lidar), cloud optical depth (sun photometer), and LWP (radiometer). As noted earlier under cloud-top height/cloud thickness, radars could be viable but work would be required for deployment on a ship.
Cloud droplet size distribution	1.9	1.4	This measurement was not discussed nor is it mentioned in the science questions.
Drizzle/rain rates (cloud base)	1.8	1.3	Below-cloud drizzle properties can be retrieved using dual wavelength techniques from any two of the following instruments: a Ka-band zenith radar, calibrated ceilometer backscatter, and a calibrated Doppler lidar backscatter (Ghate and Cadeddu 2019). While a Ka-band radar might not be feasible for unattended ship deployment, Doppler lidars and ceilometers are feasible.

Appendix E – Ship Observations Workshop Background and Guiding Questions

Participants were provided the following background information and asked to respond to the guiding questions. Responses were shared with all workshop participants before and during the workshop.

Introduction/Background to Attendees

- Based on congressional direction, the DOE Office of Science program in Biological and Environmental Research (BER) is identifying high-priority targets for a potential pilot measurement program on commercial or other non-dedicated ocean vessels traveling in regular shipping lanes. Instrumentation would likely be unattended or have only basic maintenance (i.e., cleaning) by unspecialized staff.

- In identifying targets for a potential pilot program, it is important to understand the similarities and differences between making routine observations on non-dedicated research vessels and making targeted (i.e., field campaign) measurements on dedicated ocean research vessels. Important elements to consider include:
    - Quantities/variables that can measured;
    - Types of instrumentation that can be installed;
    - Observation density, frequency, and location;
    - Opportunistic measurements rather than targeted measurements (i.e., measurements are made along the ship's planned path, rather than the path being adapted to target specific events or phenomena);
    - Co-observations needed; and
    - Science questions that can be addressed.

- A pilot measurement program would be scientifically motivated by a concise set of scientific hypotheses that are well suited to opportunistic measurements from non-dedicated ocean vessels. An initial pilot project would involve installing one or more suites of instruments on a small number of ships (perhaps only a single ship) in a particular region or shipping lane. Resources would likely be provided to a science team to conduct initial data analysis in support of the scientific questions. In doing so, the science team would also test the various components of the data acquisition system, assess data quality, and help identify gaps/difficulties/issues with all aspects of instrument performance as well as data collection, delivery, processing, and hosting.

To help us organize the workshop discussion, we ask you to draw upon your expertise and interests and provide input on some or all the following questions by Friday, February 16. If there is additional material that you think would be helpful (or questions we didn't think to ask), please feel free to include that as well.

Measurement Needs

- What are the most important variables that should be measured from **ships of opportunity** (i.e., commercial or other non-research vessels) to understand marine boundary-layer cloud, aerosol, precipitation, aerosol-cloud interactions, greenhouse gas, and radiation processes including processes relevant to marine cloud brightening?

- What scientific questions or hypotheses relevant to DOE/BER (e.g., atmospheric processes or atmospheric system predictability) could be addressed with such measurements that cannot currently be addressed?
- What are the most important regions for such measurements to be undertaken?

Measurement/Logistical Challenges

- For each of the above variables, are existing instruments suitable for unattended ship-borne operations? If not, what instrument development would be needed to make instruments suitable for unattended ship-borne operations?
- What are the logistical challenges in deploying a suite of instruments for unattended operations on commercial ships? How/where can instruments be installed on commercial ships? What power is available? What instrument maintenance is needed during or between voyages?
- Will ship exhaust impact measurements? If so, how can it be minimized or accounted for? What additional measurements might be needed?

Data

- What are the data acquisition system needs for unattended operation of the above measurements on commercial ships? How will data be obtained from the ship-borne instruments?
- What data processing/analysis/tools are needed to produce useful data sets from measurements on ships of opportunity (i.e., quality control, mapping/visualization, gridding, collocating with satellite measurements or ship traffic databases)?

Existing Activities

- What existing groups or researchers (either American or international) are deploying aerosol, cloud, and radiation measurements on research vessels?
- What existing groups or researchers (either American or international) are deploying any type of atmospheric/oceanic instruments on commercial ocean vessels?

Appendix F – Attendee Biographies

Workshop Participants

Allison Aiken, Los Alamos National Laboratory

Dr. Allison Aiken is an atmospheric chemist at Los Alamos National Laboratory (LANL) in the Earth and Environmental Sciences Division. Aiken specializes in ambient aerosol processes for climate and national security. She received her PhD in Analytical Chemistry from the University of Colorado at Boulder, specializing in high-time-resolution, in situ, particle (aerosol) mass spectrometry and has been at LANL since 2010. She is known for developing new techniques and analytical tools to measure aerosols in complex environments. Currently she is the aerosol lead for the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign that recently concluded its deployment phase by the Atmospheric Radiation Measurement (ARM) user facility in Colorado sponsored by the U.S. DOE Office of Science and the Atmospheric System Research (ASR) projects at LANL. Aiken is considered one of the World's Most Influential Scientific Minds by Thomson-Reuters as of 2014 due to her highly cited publication record (top 1%) in her field. Her elected service roles include the Board of Directors for the American Association for Aerosol Research (AAAR, 2019-22) and serving as the chair of the User Executive Committee (2021-22) for the ARM facility.

Magdalena Andres, Woods Hole Oceanographic Institute

Dr. Magdalena Andres is a Senior Scientist in the Department of Physical Oceanography at WHOI. Her research focuses on the physics of upper and deep components of eddies and western boundary currents and is motivated by three fundamental research questions: (i) how does open ocean variability manifest on the shelf and coast; (ii) how is surface variability related to deep-ocean variability; and (iii) what causes interannual-to-decadal variability in the Gulf Stream and other western boundary current systems? Her field work has been in the Kuroshio within the East China Sea and east of Taiwan, in the tropical western North Pacific, and in the Gulf Stream. Dr. Andres has participated on 20 oceanographic research cruises, including two as Chief Scientist, was the Physical Oceanography representative on the Oceanography Society (TOS) Council from 2018 to 2021, served as an expert reviewer for the Second Order Draft of the Working Group I Chapter 2 (Western Boundary Currents) of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report and was Chair of U.S. Atlantic Meridional Overturning Circulation (AMOC) Task Team 1, Observing System Implementation and Evaluation and on the Executive Committee from October 2016 through the program sunset. She is one of the lead principal investigators for the Science RoCS (Research on Commercial Ships) program at WHOI.

Tim Bertram, University of Wisconsin, Madison

Dr. Tim Bertram is a Professor of Chemistry and Affiliate Professor of Atmospheric and Oceanic Sciences at the University of Wisconsin, Madison. Research in the Bertram group is designed to provide laboratory and observation-based constraints for chemical processes occurring in the atmosphere. Of specific interest are reactions occurring at atmospheric interfaces as well as the development of novel tools to study trace gases and aerosol particles at high spatial and temporal scales. He has significant expertise in the study of sea spray aerosol. Current research studies include the production, emission, and oxidation of marine trace gases, focusing on the production of volatile organic compounds in the surface ocean, chemical reactions occurring at the air-sea interface, and bacteria-mediated production pathways for small molecules in the surface ocean. Dr. Bertram is the Associate Direct of the National Science Foundation (NSF) Centers for Chemical Innovation (CCI) Center for Aerosol Impacts on Climate and the Environment, co-editor of *Atmospheric Chemistry and Physics*, and was the principal investigator of the DOE/ARM Aerosol Growth in the Eastern North Atlantic (AGENA) field campaign.

Sarah Brooks, Texas A&M University

Dr. Sarah Brooks is a Professor at Texas A&M University, and the Director of the Center for Atmospheric Chemistry and the Environment. The focus of her research is to develop a better understanding of how natural and anthropogenic aerosol particles influence aerosol/cloud interactions on local to global scales. Using novel analytical techniques, her research group can observe ice cloud nucleation under atmospheric conditions. Through a combination of field studies and laboratory experiments, they explore how concentration, chemical composition, surface chemical reactions, and shape of aerosols impact cloud formation and properties. Dr. Brooks has conducted shipboard measurements during NSF Halocarbon Air-Sea Transect (HalocAST), Bloom Cruise, and NASA North Atlantic Aerosols and Marine Ecosystems Study (NAAMES) 1-4. She is a member of the DOE ARM User Executive Committee.

Matthew Christensen, Pacific Northwest National Laboratory

Dr. Matthew Christensen is a staff scientist at PNNL. His research focuses on quantifying the impact of natural and unnatural (biomass burning) aerosols on boundary-layer cloud processes, cloud lifetime and precipitation, and radiative forcing. He has extensive experience in remote sensing and modeling cloud systems, ship tracks and natural laboratories, and aerosol-cloud-interactions. He has been a co-investigator on several relevant field campaigns: Atmospheric Composition and Radiative forcing changes due to UN International Ship Emission regulations (ACRUISE) and the Atlantic Climate System Integrated Study (ACSIS). Dr. Christensen is also a steering committee member of Aerosols, Clouds, Precipitation and Climate (ACPC) and co-convener for several years of sessions at the American Geophysical Union fall meeting.

Christopher Cox, NOAA Physical Sciences Laboratory

Dr. Christopher Cox is a Physical Scientist with NOAA's Ocean and Atmospheric Research (OAR) Physical Sciences Laboratory (PSL). His research interests include meteorology, snow, sea ice, albedo, surface energy budget, radiation, turbulence, cloud physics, model evaluation, climate, field measurements and instrumentation, and UAS. He has conducted more than 1.5 years of fieldwork since 2019 including > 9 months arctic winter, 1.5 months equatorial Pacific, 8 months at sea, and 4 months regular work on sea ice. Dr. Cox serves on the University-National Oceanographic Laboratory System (UNOLS) Arctic Icebreaker Coordination Committee (AICC) (2022-2024), was a Panelist at the United Nations WMO Ocean Conference Side Event Polar Regions in a changing climate: ocean solutions through science and services (June 2022) and is a member of the United Nations Decade of Ocean Science (UNDOS) Safe Ocean Action Plan Working Group and the UNDOS Observing Air-Sea Interactions Strategy (OASIS) Ocean Surface Radiation Best Practices (ORBP) Consultation Working Group.

Jessie Creamean, Colorado State University

Dr. Jessie Creamean is a Research Scientist in the Department of Atmospheric Science at Colorado State University. Her research interests have focused on understanding aerosol composition and sources, with particular emphasis on aerosols that serve as seeds for cloud particle formation (i.e., aerosol-cloud-precipitation interactions). Dr. Creamean was a participant in the MOSAiC campaign, where she collected aerosol, seawater, sea ice, and snow samples to determine how biological processes from microbes – like algae and bacteria – in the water, ice, and snow are affecting atmospheric conditions that form clouds. She is the instrument mentor for ARM's ice nucleating property measurements and is a co-chair of the ASR High-Latitude Processes Working Group.

Darielle Dexheimer, Sandia National Laboratories

Darielle Dexheimer is a principal staff member in the Atmospheric Sciences department at Sandia National Laboratories and is the project lead for Sandia’s tethered balloon systems (TBS) fleet and the Lead Instrument Mentor for the ARM user facility’s TBS. She earned a Master’s in Atmospheric Science from Texas A&M University. She led ship-borne TBS missions to collect in situ aerosol and meteorological measurements off the coast of Alaska in 2017 and off the coast of Louisiana in 2018. She was also the principal investigator on a 2012 Iowa Alliance for Wind Innovation and Novel Development (IAWIND) award to deploy a prototype buoy-based TBS for offshore wind resource assessment.

Graham Feingold, NOAA Chemical Sciences Laboratory

Dr. Graham Feingold is a research scientist at NOAA's Chemical Sciences Laboratory in Boulder, Colorado. His interests lie in aerosol-cloud-precipitation interactions and implications for climate change. His focus is on process-level studies using high-resolution models and observations (aircraft and surface remote sensing) at the cloud scale (10s of meters to 10s of kms). He received his PhD in Geophysics and Planetary Sciences (summa cum laude) from Tel Aviv University in 1989. His research interests include lidar and radar remote sensing of clouds and aerosol, modeling and remote sensing of aerosol-cloud interactions ("indirect effects"), "cloud burning" or the "semi-direct effect," and cloud processing of aerosol through multiphase chemistry. He has authored or co-authored more than 200 peer-reviewed articles on these subjects. Feingold was a lead author on the IPCC AR5 Chapter 7 (Clouds and Aerosols), an associate editor of the online journal *Atmospheric Chemistry and Physics*, a contributor to the Climate Change Science Program, and a chapter author of the International Aerosol-Precipitation Scientific Assessment Project. He currently serves on the Aerosol-Cloud-Precipitation-Climate (ACPC) steering committee, and the NASA Aerosol and Cloud-Convection-and-Precipitation (A-CCP) Scientific Community Cohort (SCC) Advisory Group.

Virendra Ghate, Argonne National Laboratory

Dr. Virendra Ghate is an atmospheric scientist working at Argonne National Laboratory. His research focuses on the dynamic, thermodynamic, and radiative processes within cloudy boundary layers, with goal of improving their understanding and representation in atmospheric models. To this end, he uses data collected by several active and passive remote-sensing instruments together with radiative transfer computations and conceptual models. He has participated in multiple airborne, shipborne, and ground-based large field experiments with cumulatively more than 200 hours of experience as a flight scientist and more than eight months of sea time.

Nicki Hickmon, Argonne National Laboratory

Ms. Nicki Hickmon serves as the Associate Director for Operations for the multi-lab DOE ARM user facility. She oversees facility operations for ARM’s six observatories, including facility analysis, observing networks, data discovery, instrument operations, and strategic planning. Nicki previously worked with ARM’s second Mobile Facility (AMF2) as the AMF2 site manager for the Marine ARM GPCIO1 Investigation of Clouds (MAGIC) and the ARM Cloud Aerosol Precipitation Experiment (ACAPEX) on the *Ronald H. Brown* research vessel.

Sonia Kreidenweis, Colorado State University

Dr. Sonia M. Kreidenweis is a professor of atmospheric science at Colorado State University. Her research focuses on characterization of the physical, chemical, and optical properties of atmospheric particulate matter, and the effects of the atmospheric aerosol on visibility and climate. A particular focus area is the characterization of aerosol interactions with water vapor. She has conducted field studies in several U.S. national parks to establish the sources and characteristics of particulate matter responsible for visibility degradation, with a recent focus on the impacts of prescribed fires and wildfires. Ongoing laboratory and field studies have investigated the role of particles and of individual compounds found in particulate matter in the nucleation of cloud droplets and ice crystals, and the effects of aerosols on cloud microphysics, precipitation, and climate. Prof. Kreidenweis is a past president of the American Association for Aerosol Research and served on the executive committee of the American Meteorological Society. She is a Fellow of the American Association for Aerosol Research, American Meteorological Society, and American Geophysical Union. She is a member of the DOE Biological and Environmental Research Advisory Committee (BERAC).

Raghavendra (Raghu) Krishnamurthy, Pacific Northwest National Laboratory

Dr. Raghu Krishnamurthy is a Scientist IV at PNNL. He has significant experience in offshore field campaign deployments. He is a principal investigator for several current projects funded by the DOE Wind Energy Technology Office, including the DOE Lidar Buoy Deployments and the Wind Forecasting Improvement Project – 3, which will deploy lidars, radars, surface flux sensors, and in situ sensors on an offshore barge in 2024. He has also participated as a Senior Scientist and designed and deployed instrumentation on research ships for several campaigns funded by the Office of Naval Research including Coupled Air–Sea Processes and Electromagnetic Ducting Research (CASPER), Coastal Fog (C-FOG), and Monsoon Intra-Seasonal Oscillation in the Bay of Bengal (MISO-BOB). For MISO-BOB he developed and tested an advanced motion stabilization platform for active compensation of remote-sensing measurements; instrumented motion stabilized Doppler lidars, ceilometer, and microwave radiometer; and supported bow-mast flux sensor integration.

Gourihar Kulkarni (GK), Pacific Northwest National Laboratory

Dr. Gourihar Kulkarni is an Earth Scientist at PNNL. He works on several aerosol-cloud interaction-related projects, mainly on aerosol measurements and in situ observation analysis. He has a decade of experience in understanding the specific aerosol properties that induce droplet activation and ice nucleation and developing value-added atmospheric data products (vertical profile of CCN and INP, CCN, kappa) using DOE ARM user facility measurements (ground, remote sensing, and aircraft) for better representing the Earth's atmosphere in a climate model. He is also co-leading a pilot project to demonstrate the end-to-end treatment of aerosol delivery from the surface to the cloud base to improve planning of a marine cloud brightening strategy. In this project, he combines laboratory studies and computational approaches (computational fluid dynamics, machine learning, and large-eddy simulation) to understand the sea-salt plume transport within the boundary layer. He is a lead author on multiple journal papers, technical reports, and data products. He has mentored many interns, inspired future talent into science, technology, engineering, and math (STEM) careers, and presented at various DOE meetings, international conferences, research institutes, and community events. Before joining PNNL, he earned his PhD in Atmospheric Sciences and MS in Computational Fluid Dynamics from the University of Leeds and B. Tech. engineering degree from Karnataka University, India.

Ernie Lewis, Brookhaven National Laboratory

Ernie Lewis was originally trained as a physicist. He started at Brookhaven National Laboratory as a chemical oceanographer and participated in 10 oceangoing cruises on which he measured properties of the CO_2 system in seawater. Together with D. W. R. Wallace he wrote the program CO2SYS, which has become the standard program in the oceanographic community for intercalculation of oceanic carbon system parameters. Together with Stephen E. Schwartz, he authored the book *Sea Salt Aerosol Production: Mechanisms, Methods, Measurements, and Models—A Critical Review*, published by the American Geophysical Union in 2004. He was the principal investigator on MAGIC, which occurred between September 2012 and October 2013. MAGIC, the goal of which was to measure properties of clouds and precipitation, aerosols, radiation, and meteorological conditions in the Eastern North Pacific, involved deployment of the Second ARM Mobile Facility (AMF2) on the Horizon Lines cargo ship *Spirit* as it traversed a route between Los Angeles and Honolulu.

Lewis has been a member of the ARM User Executive Committee (UEC) and is a member of the Silver Linings Aerosol-Cloud Interactions Advisory Board, the Global Oceans Atmospheric Instrumentation Suite Science Advisory Council, and the Strategic Partnership Committee of School of Marine and Atmospheric Sciences (SoMAS) at Stony Brook University.

Gavin McMeeking, CloudSci LLC

Dr. Gavin McMeeking is an aerosol scientist and instrument developer. He has previously studied black carbon and ice nucleating particles, performed aircraft and ground measurements as part of large research campaigns, and worked for multiple commercial instrument developers. He recently co-founded an aerosol and cloud measurement company, CloudSci LLC.

Timothy Onasch, Aerodyne Research

Dr. Tim Onasch serves as a Principal Scientist and the Director of the Center for Sensor Systems and Technology at Aerodyne Research, Inc. His research interests include characterizing the physical, chemical, and optical properties of carbonaceous particles, especially emitted from combustion sources (biomass burning, diesel engines, gasoline vehicles, and jet aircraft), and understanding the transformations of these particles in the atmosphere. This work includes designing, conducting, and participating in field measurements and laboratory studies. He has led the development and application of aerosol instrumentation using mass spectrometric and optical technologies. He is a co-Chair of the ARM Aerosol Measurement Science Group (AMSG).

Markus Petters, University of California, Riverside

Dr. Markus Petters is a Professor in the Chemical and Environmental Engineering Department at the University of California, Riverside. His research studies the physical and chemical properties of particles between 0.01 and 10 µm with a focus on understanding phase transitions. His work spans instrument development, laboratory measurements, field observations, and process-level model development. He is a co-chair of the ASR Aerosol Processes Working Group.

Patricia Quinn, NOAA Pacific Marine Environmental Laboratory

Dr. Patricia Quinn is an atmospheric chemist at the NOAA PMEL. She is currently acting Director for the Ocean Climate Research Division. Her research focuses on the effects of atmospheric aerosol particles on air quality and climate. Dr. Quinn has participated in research cruises since 1986, studying a broad range of aerosol types ranging from remote marine aerosol in the Arctic and Antarctic to pollution aerosol in the Houston Ship Channel and the oil and gas fields of Utah’s Uintah Basin. She has also been recognized as a highly cited researcher in Web of Science (2016, 2017, and 2018) and selected as an American Geophysical Union Fellow in 2010 and an American Association for the Advancement of Science (AAAS) fellow in 2019.

Lynn Russell, Scripps Institute of Oceanography

Dr. Lynn Russell is a Distinguished Professor of Atmospheric Chemistry at the Scripps Institution of Oceanography at the University of California, San Diego. Her research group investigates the behavior of aerosol particles in the Earth’s atmosphere under both pristine marine and polluted urban conditions. Measuring the properties of atmospheric structure and its chemical constituents is an important part of these investigations, for which the Russell group has developed instruments for airborne and shipboard observations. Dr. Russell’s group has developed significant expertise in using synchrotron radiation to measure organic composition in individual organic particles with soft X-rays. Field projects are an important part of their research effort, providing evidence of the role of aerosol particles in atmospheric chemistry, meteorology, and radiation. Interpreting the results of field projects involves both analysis with numerical models of aerosol evolution and laboratory investigations.

Dr. Russell is principal investigator of the Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE), a recent ARM Mobile Facility deployment.

Shawn Smith, Florida State University

Shawn Smith is a Senior Research Associate in the Center for Ocean-Atmospheric Prediction Studies at Florida State University (FSU). He has significant experience in data management for shipborne observing systems. Over the past two decades, he has been director of the Marine Data Center at FSU, which has a focus on the quality evaluation, distribution, and archival of underway weather and surface ocean data from research ships. He has led the Shipboard Automated Meteorological and Oceanographic System (SAMOS) Initiative since 2005, is a co-principal investigator on the Rolling Deck to Repository project, which manages underway data for the U.S. Academic Research Fleet, and is a contributor to the WHOI-led Science RoCS. From 2017-2020, he was the Vice-Chair (and acting chair for about a year) of the Global Ocean Observing System Ship Observation Team. Finally, he has contributed to several NASA Jet Propulsion Laboratory-led projects to develop the Cloud Data Match-up Service and Science Data Analytics Package distributed by the Apache Software Foundation.

Armin Sorooshian, University of Arizona

Dr. Armin Sorooshian is a Professor, University Distinguished Scholar, and da Vinci Fellow in the Department of Chemical and Environmental Engineering at the University of Arizona, with courtesy appointments in Hydrology and Atmospheric Sciences, the College of Optical Sciences, and the College of Public Health. His research focuses on the effect of aerosol particles on the environment, clouds and rainfall, climate, and public health/welfare. A suite of synergistic methods are used for this research, including laboratory experiments, ground and airborne field measurements, modeling, and remote-sensing observations. Since 2004, Dr. Sorooshian has participated in 15 airborne field projects, including six as a mission principal investigator with the Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS) Twin Otter (sponsored by the Office of Naval Research). Currently, Armin is involved with a multi-year NASA project called the Cloud, Aerosol and Monsoon Processes Philippines Experiment (CAMP^{2}EX) and is the principal investigator of a NASA Earth Venture Suborbital-3 (EVS-3) mission called ACTIVATE. He currently serves on the Scientific Committee for Oceanographic Aircraft Research (SCOAR; University-National Oceanographic Laboratory System), the American Association for Aerosol Research Awards Committee, and on the Editorial Board for *Atmospheric Chemistry and Physics*.

Kerry Strom, Woods Hole Oceanographic Institute

Kerry Strom is the Senior Manager for Marine Operations at Woods Hole Oceanographic Institute (WHOI). Her responsibilities include planning and scheduling global voyages for three vessels and three submersibles through the University-National Oceanographic Laboratory System (UNOLS); coordinating with other UNOLS ship operators for oceanographic missions; and maintaining communications with federal funding agencies to insure adequate information flow regarding schedules, science users, and funding levels. She works with key people in the National Deep Submergence Facility, Shipboard Science Support Group, Ship Operations to facilitate scheduling, clearances, and logistics. She also prepares international research clearances through the U.S. State Department to coordinate and follow up clearance applications. She is Co-Founder of Science Research on Commercial Ships (Science RoCS) Reporting to the Vice President for Marine Facilities and Operations.

Ms. Strom has 24 years of international, maritime operations experience. Her expertise includes knowledge of oceanographic vessels/human-occupied vehicles/autonomous underwater vehicles, seismic operations, vessel planning and scheduling, logistics management, dry-docking, procurement, cost management, accounting, agency services, government agencies, stevedoring, terminal/ port authority activities, and chartering.

Adam Theisen, Argonne National Laboratory

Adam Theisen is the Instrument Operations Manager for the ARM user facility, overseeing a team of 80+ instrument experts as they support the facility. He has previously worked with ARM's Data Quality Office, working with data from ARM's shipborne campaigns as well as developing machine learning-based approaches to detect ship exhaust contamination in aerosol measurements. Additionally, he leads the Atmospheric data Community Toolkit (ACT), an open-source Python library for working with research-focused, time-series-based data sets.

Janek Uin, Brookhaven National Laboratory

Janek Uin got his PhD in physics for research on electrical aerosol spectrometers and techniques for their calibration, including development of new methods for producing high-quality calibration aerosols. In addition to laboratory research, he has managed setting up remote measurement stations and participated in field campaigns with the interest in studying atmospheric secondary new particle formation in the particle size range down to 1 nm. Janek serves as the ARM instrument mentor for a variety of instruments (CCN, HTDMA, nephelometer, ultra-high-sensitivity aerosol spectrometer [UHSAS]). He has previously deployed aboard an ice-breaker in the Arctic as part of the MOSAiC initiative to support ARM's aerosol measurements.

Robert Wood, University of Washington

Dr. Robert Wood is Professor of Atmospheric Sciences at the University of Washington. His research focuses upon understanding processes controlling clouds in the Earth's atmosphere and the roles that clouds play in determining climate variability and change, the formation of rain, and how tiny aerosol particles (both natural and anthropogenic) interact with clouds and help determine their physical and radiative properties. Dr. Wood also conducts research to understanding the potential for deliberate brightening of marine low clouds to offset greenhouse warming by augmenting the natural aerosol population. Dr. Wood's research uses a combination of observational data collected with aircraft, satellites, and from ground-based remote sensing, together with numerical and theoretical models.

Dr. Wood served as principal investigator of the Variability of the American Monsoon Systems (VAMOS) Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx), a major international field experiment focusing on the interactions of aerosols and clouds over the Southeastern Pacific Ocean. Dr. Wood also served as deputy principal investigator on a NASA Earth Ventures Suborbital field program (Observations of Aerosols above Clouds and their Interactions [ORACLES]) to examine the effects of biomass burning aerosols on clouds over the Southeastern Atlantic Ocean. Dr. Wood was awarded the 2001 L. F. Richardson Prize from the Royal Meteorological Society and the 2010 Henry Houghton Award from the American Meteorological Society, "For advancing understanding of the interactions between cloud droplets, aerosols, radiation and precipitation in marine stratocumulus."

Xiaoli Zhou, NOAA Chemical Sciences Laboratory

Dr. Xiaoli Zhou is a Research Scientist in the Cloud, Aerosol, and Climate Group of the NOAA Chemical Sciences Laboratory. Her research interests include boundary-layer cloud physics and dynamics and their interaction with aerosol and precipitation from microphysical scale to mesoscale. Her research involves using large-eddy model simulations and synergetic remote-sensing observations from both ground-based and space-based sensors to help improve representation of boundary-layer clouds in global climate models. She received the Cloud Feedback Model Intercomparison Project (CFMIP) Early Career Scientist Award in 2021 for her presentation on “Sea surface temperature control on the aerosol-induced brightness of marine clouds over the North Atlantic Ocean – Implications for cloud feedback in a future warmer climate.” Dr. Zhou is a co-investigator on a current ASR research project, “Aerosol-cloud interactions centered on MAGIC: Insights from measurements and Lagrangian large eddy simulation.”

Interagency Program Manager Observers

Victoria Breeze, NOAA

Dr. Victoria Breeze is a Program Manager in the NOAA Climate Program Office. She co-manages NOAA’s Earth Radiation Budget (ERB) program, a multi-year research initiative to conduct fundamental research on the stratosphere and marine boundary layer, investigate natural and human activities that might alter the reflectivity and radiative balance of the atmosphere, and study the potential impact of those activities on the Earth system.

Gregory Frost, NOAA

Dr. Gregory Frost leads NOAA Chemical Sciences Laboratory research using observations and models to understand the impacts of atmospheric emissions and chemistry on air quality, weather, and climate. Dr. Frost is the Atmospheric Composition and Chemistry Liaison in NOAA’s Office of Oceanic and Atmospheric Research (OAR) and leads collaborative activities with other NOAA line offices. He co-manages the NOAA Earth’s Radiation Budget Initiative, a congressionally directed research program investigating natural and human activities that may alter the reflectivity of the atmosphere and impact the Earth system. Dr. Frost led the 2020 value assessment of an atmospheric composition capability on NOAA’s Geostationary Extended Observations (GeoXO) Mission and is the User Applications Scientist for GeoXO’s Atmospheric Composition Instrument, ACX. He oversees transitions of OAR's atmospheric composition research innovations into the Unified Forecast System.

Hal Maring, NASA

Dr. Hal Maring works at NASA Headquarters in Washington, DC as the Program Manager for NASA's Radiation Sciences Program. Previously Hal was part of the faculty of Marine and Atmospheric Chemistry at the University of Miami, from 1993 to 2005. Hal received his BS (1977) from the University of Michigan, and his PhD (1985) from the University of Rhode Island in Oceanography. He was a Postdoctoral Fellow at the California Institute of Technology from 1985 through 1987 and then was a Marine Research Scientist at the University of Rhode Island from 1988 through 1992.

Workshop Organizers

Sally McFarlane, DOE SC/BER

Dr. McFarlane is a program manager in the BER program within DOE’s Office of Science (SC). Dr. McFarlane manages the Atmospheric Radiation Measurement (ARM) user facility, which provides the climate research community with observations from fixed and mobile atmospheric observatories to improve understanding of the fundamental processes governing the interactions among aerosols, clouds, precipitation, and radiation. Dr. McFarlane is also the portfolio manager for BER’s participation in the DOE SBIR/Small Business Technology Transfer (STTR) program. Dr. McFarlane is actively involved in interagency efforts focused on observations including the U.S. Global Change Research Program (USGCRP) Interagency Working Group on Observations, the Interagency Coordinating Committee for

Airborne Geoscience Research and Applications (ICCAGRA), and the Interagency Council for Advancing Meteorological Services (ICAMS) Committee on Observational Systems. Prior to joining DOE Headquarters, Dr. McFarlane was an active research scientist with over 50 peer-reviewed publications focusing on the use of remote-sensing observations and radiative transfer models to improve understanding of the radiative effect of clouds and aerosol on the Earth's atmosphere and to evaluate cloud and climate models. Dr. McFarlane is a Fellow of the AAAS.

Shaima Nasiri, DOE SC/BER

Dr. Nasiri is a program manager in the BER program within the DOE Office of Science (SC). Dr. Nasiri manages the ASR portfolio, which supports atmospheric process research to improve understanding of the fundamental processes governing the interactions among aerosols, clouds, precipitation, and radiation. Dr. Nasiri represents DOE on several interagency committees and working groups including the ICAMS Committee on Research and Innovation and co-chairing the U.S. Group on Earth Observations (USGEO) Satellite Needs Working Group. Prior to joining DOE Headquarters, Dr. Nasiri was an associate professor of atmospheric sciences at Texas A&M University where her research primarily focused on satellite-based remote sensing of clouds and aerosols, retrieval algorithm development, and radiative transfer to better understand how clouds and aerosols interact with radiation to affect the climate. Dr. Nasiri is a Fellow of the American Meteorological Society.

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